THE SEDIMENT YIELD RESPONSE TO LAND USE INTENSIFICATION IN A HUMID, TROPICAL CATCHMENT:

THE TULLY RIVER CATCHMENT, NORTHEAST QUEENSLAND, AUSTRALIA

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A thesis submitted for the degree of Doctor of Philosophy

of the

Australian National University.

March, 1994.

Except where otherwise acknowledged, this thesis represents my own, original work.

David Neil
March, 1994

ACKNOWLEDGEMENTS

Many people have assisted in many ways in the course of this work.

I wish first to thank my principal supervisor, John Chappell, for encouragement, advice, support, inspiration, flexibility and patience. It was a long time ago, but my recollection is that the idea for this research developed from a discussion with Bob Wasson, my co-supervisor, who I also thank for encouragement, advice, support and inspiration over nearly ten years (not all on this project).

Three colleagues deserve special mention for their support and encouragement. Peter Isdale, Australian Institute of Marine Science, supported the project from the outset and it could not have been done without his support and that of AIMS. Stan Newman, formerly of the Australian Institute of Nuclear Science and Engineering, spent many days and nights at Lucas Heights Research Laboratories, assisting with the ion beam analysis and running the spectral analysis programs. He did far more than was asked of him, and then assisted even further. Bofu Yu has been a sounding board for ideas, a source of ideas, wrote and ran the computer program to run the median test analyses in Chapter 4, has helped make sense of ideas about rainfall erosivity, and has provided intellectual stimulation and support.

High quality technical support was given by Jim Caldwell, Bio & Geo, ANU, who assisted with the X-ray diffraction analyses and analysed water samples, and Rob Sageman, CSIRO Division of Water Resources, who carried out numerous analyses of stream water chemistry. Ted Daniel, AIMS, organised the coral coring research cruise, gave a great deal of invaluable advice, and assisted with the coral core processing and running of "Fluorac". All were generous with their time and knowledge. Alex Katsaros (AINSE) and Alec Kroll (ANSTO) also provided valuable technical assistance.

A great deal of administrative and logistical support was provided by Damien Kelleher, Carlo Martinello, Marcia Murphy and Eugene Wallensky of Bio & Geo, ANU, for which I am most grateful. I wish to thank all of my colleagues in Bio & Geo for friendship, support, and intellectual stimulation over many years, and wish particularly to mention the support of Paul Hesse and Donald Walker. I also thank all those friends and colleagues who have provided help and support along the way.

Several people generously offered me the hospitality of their homes in Canberra (particularly John Chappell and Helen McClagan, Marcia Murphy and Paul and Tsukimi Hesse), in Townsville (Peter and Cheryl Ridd, and Peter and Val Valentine) and in Tully (Peter and Denise Newton).

Generous support for this research came from the Department of Biogeography and Geomorphology, Australian National University, the Australian Institute of Marine Science, and the Australian Institute of Nuclear Science and Engineering. The Great Barrier Reef Marine Park Authority provided an Augmentative Research Grant. I am very grateful for all of this support.

Staff of numerous organisations have given assistance and support in many ways. These include Australian Institute of Marine Science (Joe Baker, Peter Ridd, Eric Wolanski and others), Australian Institute of Nuclear Science and Engineering and Australian Nuclear Science and Technology Organisation (David Cohen, Eric Clayton, Mike Hotchkiss, Roger Gammon, Jean Breakspere and others), James Cook University Department of Geography and Sir George Fisher Centre for Tropical Marine Research, Queensland Water Resources Commission, Queensland Forest Service and Queensland Departments of Railways and Main Roads, Bureau of Sugar Experiment Stations (Tully), Tully Mill, Tully River Station (Richard and Gay Luck), Newton Engineering, Tully, for generous engineering support and Newton's Bait and Tackle, Tully, for scuba equipment. I am most grateful to all of them.

Finally I wish to thank my family, particularly Mum and Dad, for their support for as long as I can remember.

This thesis is dedicated to Kelly who never wanted to go to Canberra, but enjoyed Tully.

ABSTRACT

The sediment yield response to land use intensification in the Tully River catchment and adjacent Rockingham Bay, northeast Queensland, was investigated with the particular purpose of examining the proposition that massive corals contain long term records of sediment yield. Land use in the 1 685 km^2 catchment is largely sugar cane and banana cultivation and beef cattle fattening on alluvial plains and rainforest on steeplands.

Spatial patterns of stream water quality in relation to catchment characteristics were investigated and were better correlated with the proportion of sub-catchments cleared for agriculture than with other physiographic characteristics. Suspended sediment concentrations in the Tully River are generally consistent with those reported for similar terrains elsewhere. Estimated suspended sediment yield for the Tully River in the 1990 water year was 71 $t.km^{-2}$. A sediment yield history, using this yield as a reference point, was reconstructed by space-time substitution using the spatial relationship between land use and stream water quality, and climate and land use histories developed for the catchment. Potential sediment yield is inferred to have increased by about 240 % in response to land use intensification during the period 1926-1990. However, a decline in rainfall erosivity during this period suggests that the actual sediment yield may have declined by up to 40 %.

Sediment plume movement from the river mouth toward island fringing reefs was monitored. During most flood events, southeasterly winds and the geostrophic current force sediment plumes to move northward, close inshore. Suspended sediments of fluvial origin at island fringing reef sites will generally be the result of tidal recirculation, rather than the direct effect of the river plume. Bottom sediment resuspension, although generating lower sediment concentrations than river plumes, occurs more frequently.

The relationship between the Tully River stream flow record and skeletal fluorescence in massive *Porites* corals from Rockingham Bay was examined and a strong correlation was found between fluorescence and annual discharge. Hence, Tully River sediment outflow may be recorded by the corals. The fluorescence record did not accurately correlate with stream flow at monthly or other sub-annual time scales. The nature of the mixing processes which blur the sub-annual record was not identified.

Elemental and mineralogical analyses of acid-insoluble fine-grained particulate residues show that the Rockingham Bay corals contain kaolin,

which is the dominant mineral in Tully River sediment plumes. Corals also contain fine particles of biogenic silica which is believed to be resuspended from the local sea bed.

PIXE and PIGME (proton-induced X- and gamma-ray emission) methods were used to examine sediment within Porites from Rockingham Bay. Al, Si and Fe were used as sediment tracers. PIXE/PIGME methods provide measurements along continuous profiles and, in principle, have sufficient resolution to measure Al, Si and Fe at the concentrations measured in bulk samples. However, a record of sediment yield from the Tully River was not obtained by these methods because:

i. Separation of diagnostic from irrelevant elements was not achieved using the ion beam method. In particular, Al and the strong Mg signal could not be separated in PIGME analyses.

ii. None of the time series for Al/Mg, Si or Fe show significant relationships with the Tully River sediment yield time series.

iii. Detrital contamination occurs in the coral skeleton due to the effects of endolithic organisms and uncertainties exist regarding modes of sediment inclusion in coral.

Results suggest that a high resolution record of suspended sediment concentrations which can be quantitatively related to fluvial sediment yield at sub-annual time-scales is unlikely to be obtained from coral skeletons using scanning methods. However, extraction of acid-insoluble residues in annual bands has some promise, and further investigation of this possibility is recommended.

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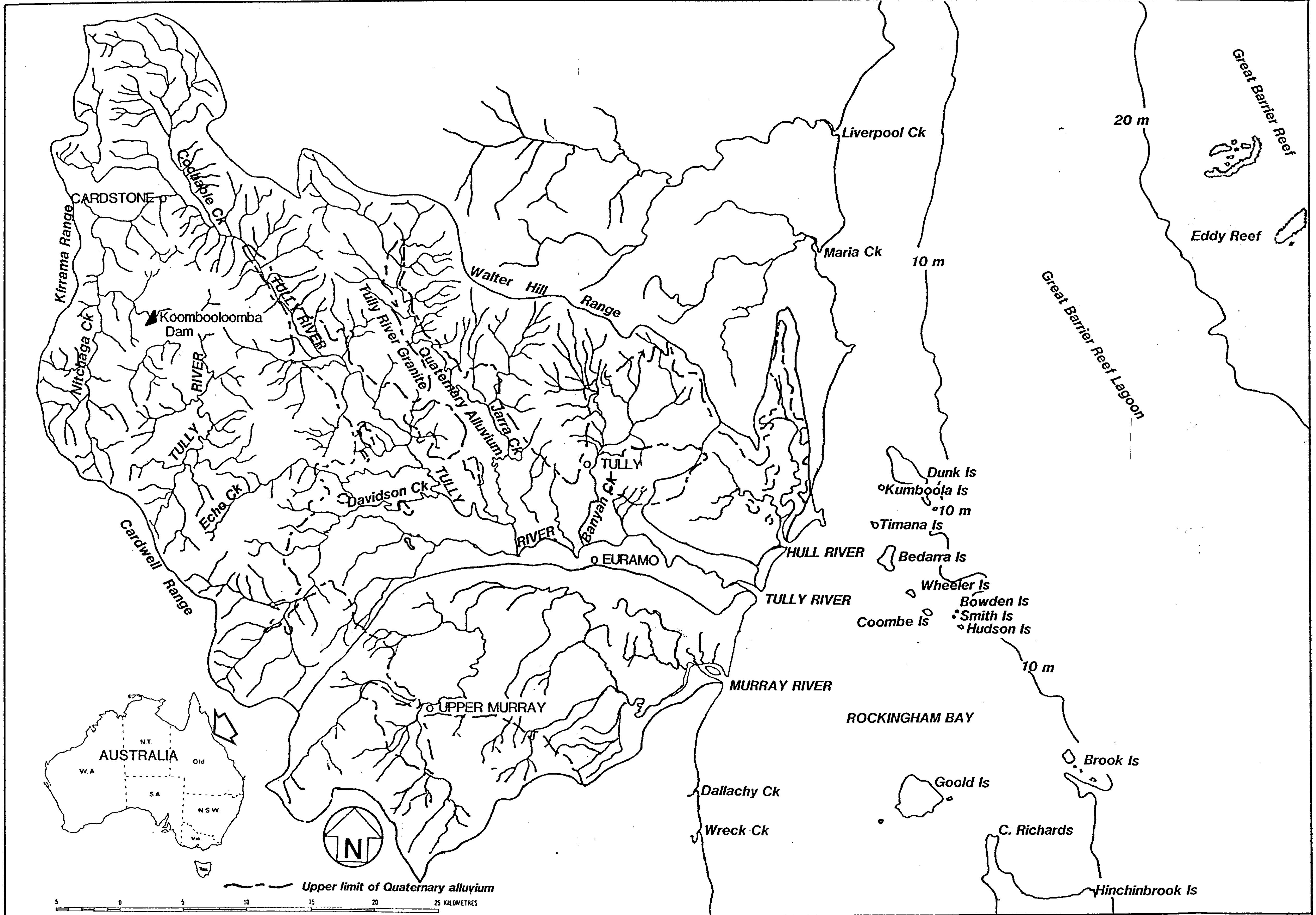


STUDY AREA: Tully River Catchment and Rockingham Bay, Northeast Queensland, Australia

CHAPTER ONE

INTRODUCTION

CONTENTS

1.1	BACKGROUND TO THE STUDY
1.2	SELECTION OF THE STUDY SITE
1.3	RESEARCH PLAN AND PLAN OF THE THESIS

1.1 Background to the Study

In a recent review, Meybeck (1992: 94) suggested that "enhancement of erosion by man's activities is one of the major, and probably one of the earliest, influences of man on the environment". Also, "..almost any kind of activity (agriculture, urbanisation, communication, mining, industry, etc.) leads to an increase in suspended matter in surface waters". Johannes (1975) observed that "exposure of reefs to brackish, silt-laden water associated with flood runoff has probably been the single greatest cause of reef destruction historically".

From an environmental management perspective, the impacts of land use intensification must be understood within three interconnected environments - terrestrial, fluvial and marine. In the terrestrial environment, accelerated soil erosion and associated loss of nutrients often lead to decreased yields of commercial and subsistence crops. Deposition of the eroded soil may result in burial of productive soils elsewhere in the catchment. Geomorphic and ecological change in stream channels affected by land use intensification can impact on commercial, recreational and subsistence fisheries, the viability of industrial processes and the treatment cost of water for domestic and industrial uses, and can also increase the frequency and magnitude of flooding. Terrigenous sediments transported into marine ecosystems can adversely affect the viability of industries such as fisheries and tourism, and can significantly alter the composition and structure of biological communities. In all three of these environments the effects of increased erosion, deposition and sediment in suspension may also be critical in determining the viability of natural, or "semi-natural" habitats in both the short and long term.

The importance accorded to increased suspended sediment concentrations in streams has increased over recent years, with greater understanding of the role of sediments in nutrient transport, and of the implications of sediment-nutrient interactions for downstream eutrophication of freshwater and marine ecosystems. In the case of tropical marine ecosystems, sedimentation and eutrophication can lead to the destruction or modification of coral reefs, followed by reduction or loss of fishery and tourism resources and of conservation values.

In Australia, the tropical marine region includes the Great Barrier Reef, the most extensive system of coral reefs on the planet. Soil erosion and catchment sediment yield records of a length commensurate with the inherent temporal variability of geomorphic processes are a fundamental requirement for management and planning of this and other coral reef regions. However, in the the Great Barrier Reef region and in most other tropical areas such records are few. A distinction between tropical and equatorial streams, given the relatively low inter-annual stream flow variability in the latter, is appropriate.

It is of importance in terms of geomorphic processes and terrestrial and aquatic ecosystems management to know the mean annual sediment yield, the intra- and inter-annual variability of sediment yield and the sediment yield response to land use intensification in tropical catchments. Given the paucity of data, however, techniques for reconstructing sediment yield histories are of particular importance. One of the most effective of such techniques is reservoir sedimentation analysis which can be used to determine the average sediment yield over the period since reservoir construction. A sedimentation time series can be obtained by detailed sedimentological analysis with the aid of techniques such as palynology and ^{137}Cs dating.

Reservoir sedimentation studies have a number of important limitations, particularly in tropical areas. These include:

(i) Site location is determined by engineering and topographic considerations. Consequently, reservoir catchments are often morphologically atypical with a transportational, rather than a depositional, stream reach at the downstream end of the catchment.

(ii) As a result of site suitability considerations, it is not practical to construct a reservoir which includes the entire catchment of a stream discharging to the sea. Therefore, there is an inherent bias in the physiographic characteristics of catchments which can be analysed using this method. Coastal embayments are unable to provide a record of sediment yield with the same chronological reliability as reservoir sediments because of sediment resuspension by wave action, disturbance by bioturbation, and uncertainties regarding trap efficiency.

(iii) The initial sediment yield response to land clearing is not usually available in the reservoir sedimentation record because dam construction generally occurs only after an area has been settled.
(iv) Infrastructure development, including dam construction, has generally occurred more recently in tropical than in temperate environments. Therefore, only a relatively short-term record is available.
(v) Lower population densities in Australian tropical areas mean that few dams have been constructed.
(vi) In the wet tropics, dam construction for reticulated water supply is generally unnecessary because of the ready availability of water from perennial streams in high runoff catchments. This also means that few dams have been constructed.
(vii) Difficulties and uncertainties often exist in resolving reservoir sediments to an annual sedimentation increment with confidence.
(viii) In order to interpret sediment yield histories from prior to land use intensification, a natural sediment yield baseline is required against which the sediment yields after land use intensification can be compared. Interpretation of these data requires information on climatic and hydrological conditions for the entire period of the sediment yield record.

Although some of the above limitations apply in temperate Australia, the number and location of reservoirs is sufficient to provide time series records of sediment yield for a wide range of climates, lithologies and land uses. The limitations outlined above indicate that an alternative technique must be found for reconstruction of sediment yield histories in tropical Australia. Such a technique would also be applicable to tropical regions elsewhere.

Corals of the *Porites* genus with a massive growth form are useful environmental recorders by virtue of their incorporation, at the time of calcification, of various constituents of the waters in which they are growing. They have structural and distributional characteristics which resolve many of the limitations of reservoir sedimentation techniques.

Porites colonies have the following characteristics:

(i) They are tolerant of high turbidity waters and grow in nearshore marine areas. They are widely distributed throughout the Indo-Pacific and Atlantic coral reef provinces. As such, they potentially resolve limitations (i), (ii), (v) and (vi) above.
(ii) They grow to a great age, estimated to be in the order of 1 000 years for some colonies, potentially resolving limitations (iii) and (iv).
(iii) They have readily identifiable annual growth increments of sufficient size (c. 9-10 mm and often > 15 mm) to allow resolution to a sub-annual time-scale, potentially resolving limitation (vii).

(iv) In nearshore environments they contain annual bands which fluoresce under ultra-violet light. The fluorescence intensity is correlated with flow from adjacent streams, potentially resolving limitation (viii).

These characteristics of massive *Porites* colonies and their application as environmental recorders are described in more detail in Chapters 6 and 7.

If massive coral colonies contain records of the sediment yield from coastal catchments over centuries, particularly at a resolution of annual or better, they have the potential to provide a powerful tool for geomorphic analysis (Fig. 1.1) and a rational basis for terrestrial and aquatic ecosystem management. The literature contains research findings which indicate that such an approach is feasible (e.g. Barnard, Macintyre and Pierce, 1974; Cortes and Risk, 1985) and others which indicate the contrary (e.g. Goreau, 1977a, b; Benninger and Dodge, 1986; Davies, 1992, in prep.; Budd, Mann, and Guzman, 1993). It is this proposition, that massive corals contain long term records of sediment yield, which this study seeks to investigate. Given the nature of the skeletal UV fluorescence record (Isdale, 1984) it is anticipated that a sediment yield record with a resolution of one month is possible.

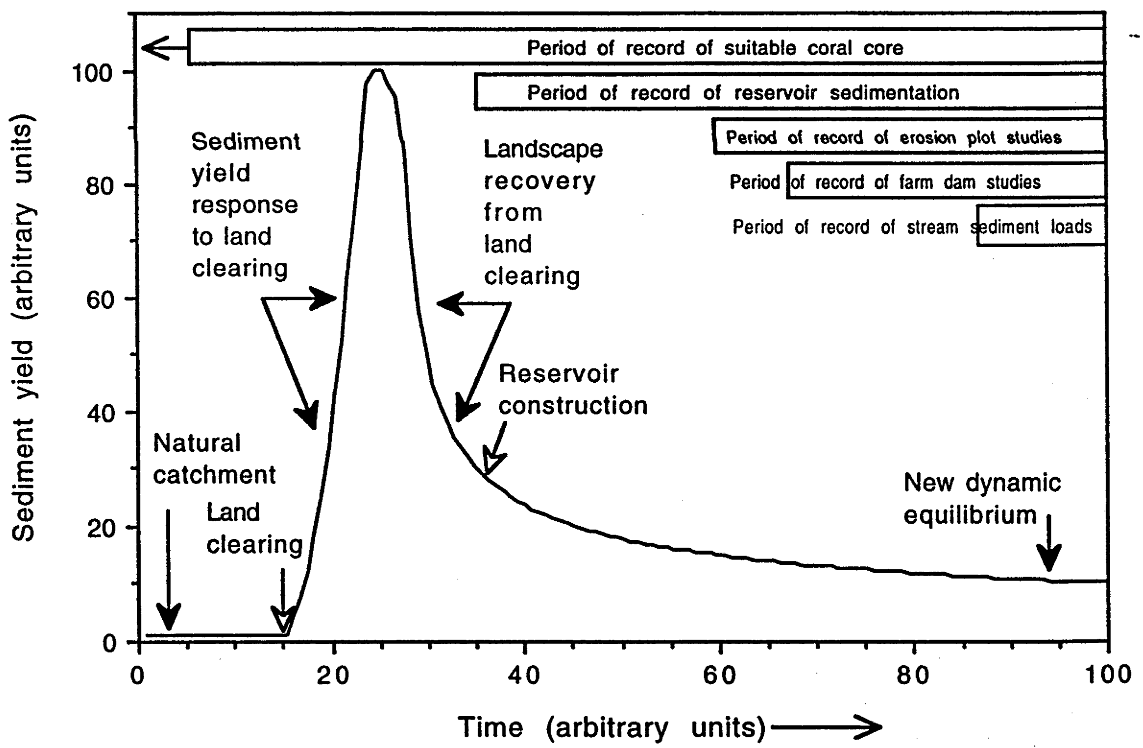


Fig. 1.1
Hypothetical curve illustrating sediment yield response to land clearing, and the relative time-scales of several methods of determining sediment yield. The hypothetical model is based on studies in southeastern Australia. In tropical areas much of the land clearing also occurred during the late 19th century, but the sediment yield records available are generally of shorter duration than those illustrated.

1.2 Selection of the Study Site:

Characteristics of an appropriate study site include attributes of the terrestrial and marine environments, the climate and the land use history. The Tully River, discharging to Rockingham Bay at 18° S latitude in the humid tropics of northeast Queensland, Australia, was selected as an appropriate site for the investigation of the sediment yield response to land use intensification and the potential of massive corals to record this response. The reasons for this choice include:

(i) The Tully catchment has a high mean annual rainfall (4 200 mm at Tully town) and a high runoff coefficient (0.74) ensuring that high stream flows, with the potential to transport suspended sediments into the marine environment, occur frequently. The Tully River has low inter-annual stream flow variability, minimising the contribution of hydrological variability to changes in the quantity of sediment transported into the marine environment. As a result, the effect on sediment yield of land use intensification should be more readily discriminated from the hydrological noise.

(ii) Continental islands with fringing reefs lie over a wide arc (105°) from the Tully River mouth, and at varying distances from it. Consequently, variations in the direction of river plume movement will not necessarily result in the plume bypassing the coral colonies selected for analysis. Variation in distance also means that, if an extreme flood results in coral mortality, not all colonies sampled are likely to have been affected. The island fringing reefs of Rockingham Bay are sufficiently close to the river mouth that sediment plumes from the Tully River are likely to reach them during major floods.

(iii) Agricultural land use in the Tully catchment is about evenly divided between sugar cane and, increasingly, banana cultivation, and improved pasture for cattle fattening. A little over twenty percent of the catchment is used for these purposes, most of the remainder retaining the natural rainforest cover. This area of land clearing is sufficient to generate a substantial increase in sediment yield. There were two periods of cane land expansion (mid-1920s and late-1970s) and a period of large-scale land clearing for pasture in the early-1960s. The occurrence of several periods of land use intensification means that there is effectively a sample of three sets of sediment yield responses to test the effectiveness of the massive corals as sediment yield recorders. Furthermore, the relatively recent initial change in land use compared with other catchments in the wet tropics (about 40 years later than the Johnstone and Herbert Rivers to the north and south, for example) requires a forty year shorter coral record. This is likely to be an important consideration given that *Porites* colonies in turbid, nearshore waters infrequently attain the great size common in clear, offshore waters.

(iv) Adequate historical sources and annual data collected by the Australian Bureau of Statistics are available to construct an acceptable history of land use in the Tully catchment. There has been little land use change on the continental islands where the fringing reefs are located. Most of these islands are National Parks. Consequently, changing sediment yields from the islands due to anthropogenic effects are not an important factor in the analysis.

(v) The Tully River catchment also has several logistical advantages. The high rainfall and runoff yield a large discharge volume from a relatively small catchment (1 685 km^2) which is advantageous in terms of the time and expenditure required for field work. The generally linear form of most of the course of the Tully River and the existence of roads along both sides of the river make stream water sampling of most of the significant tributaries to the river logistically feasible.

The major disadvantages of the Tully River are that continuous rainfall data for a single site is available only from 1925, and continuous recording of stage in the Tully River is only available since 1972. Given the availability of the fluorescence record in the corals, these disadvantages were considered to be outweighed by the many advantages of this site for the proposed research.

A more detailed description of the characteristics of the Tully River catchment and of Rockingham Bay is given in Chapter 2.

1.3 Research Plan and Plan of the Thesis:

The objective of this research is to assess the potential of inclusions in the skeleton of annually-banded massive corals to provide a high temporal resolution record of the sediment yield response to land use intensification in a humid tropical catchment.

The research plan for this investigation is most efficiently outlined by following the sequence of presentation in the following chapters. A summary of this sequence is presented in Fig. 1.2.

Chapter 2 describes the characteristics of the study area of most relevance to the study objective. The geology, geomorphology, soils, climate and vegetation of the terrestrial environment, of both the mainland and islands, are documented, emphasising those characteristics of most relevance to catchment sediment yield. A general description of the climatic and oceanographic characteristics of Rockingham Bay is also presented,

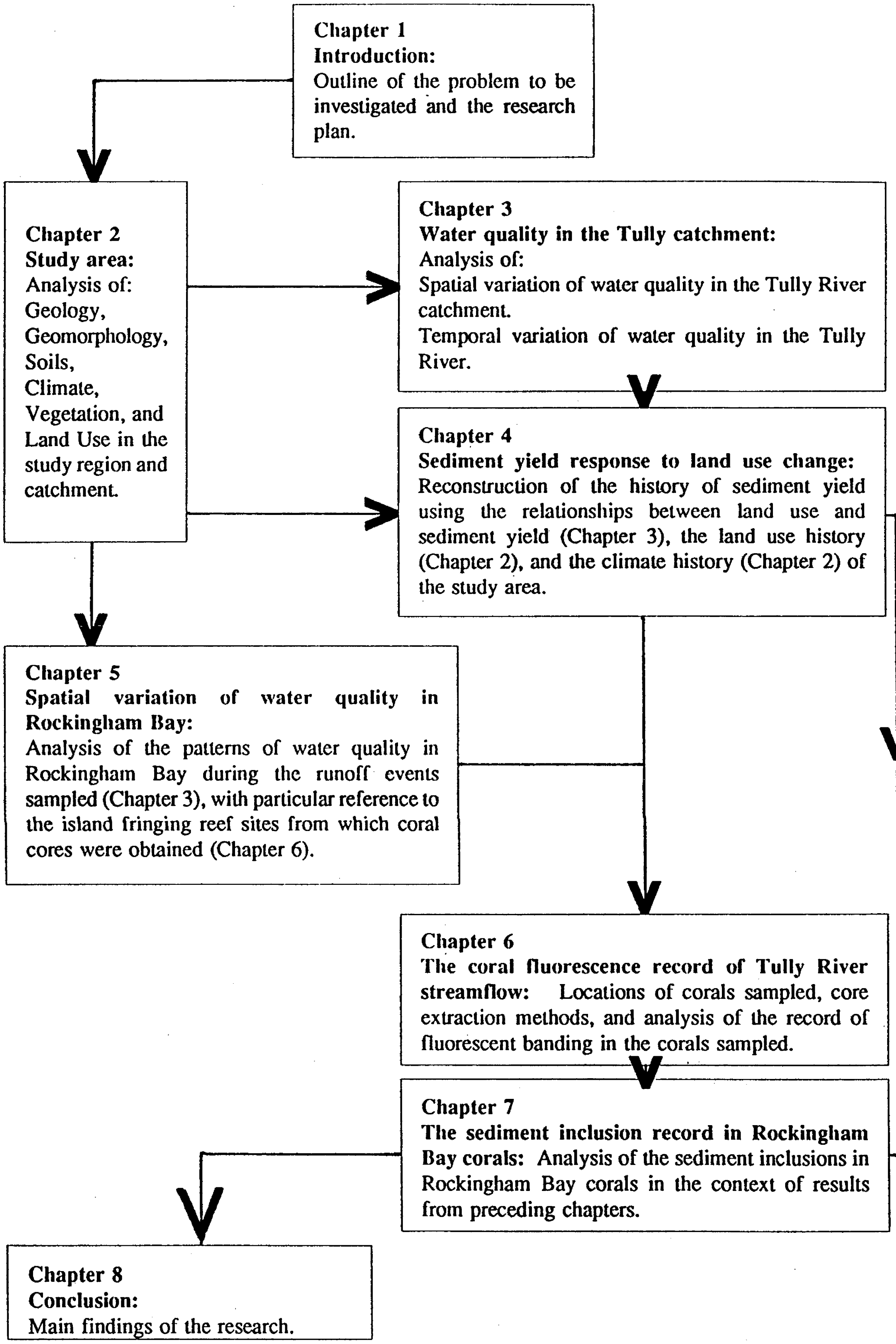


Fig. 1.2
Research plan

emphasising wind and wave climate which influence the pattern of sediment plume movement and resuspension of bottom sediments. A land use history of the study area is compiled from historical sources and Australian Bureau of Statistics annual agricultural census data. The changing area under various types of vegetative cover, changing land management practices, and the history of agricultural inputs, particularly fertilisers, are emphasised.

Chapter 3 presents an analysis of water quality in the Tully River catchment, emphasising suspended sediment concentrations. This analysis is approached in two ways. Firstly, the temporal variation in water quality in relation to stream flow over two sampling periods (1987-88 and 1990) is described for the Tully River at the Queensland Water Resources Commission (QWRC) stream gauging station at Euramo (AMTD = 17.5 km). Additional analyses of the suspended particles were undertaken in order to clarify the relationship between observations at this site and processes in the catchment. Secondly, spatial variation in water quality within the Tully catchment was investigated. Sub-catchments within the Tully catchment were selected in order to obtain a wide range of attributes, including land use. Water quality in these sub-catchments was analysed in relation to these attributes.

A time series of the sediment yield response to land use change in the Tully catchment is developed in Chapter 4. The relationships between land use and water quality identified in the spatial analyses in Chapter 3 were used to develop estimates of the increase in suspended sediment concentrations, with respect to natural catchments, which occur for increasing percentages of catchment cleared for different land uses. These 'increase factors' were standardised against the known sediment yield (determined in the temporal variation analysis in Chapter 3) and the known land use (determined in Chapter 2) for a given year (1990). A time series of estimated absolute annual sediment yield for the Tully catchment was then constructed using the land use history documented in Chapter 2. This sediment yield time series was then recalculated and further refined using the climatic history analysis developed in Chapter 2.

Patterns of sediment plume distribution in Rockingham Bay during the stream water sampling periods are investigated in Chapter 5. The spatial extent, direction of movement and water quality in the sediment plumes generated by the Tully River are interpreted in relation to the characteristics of stream flow and water quality in the Tully River at the time. These investigations emphasise the relationship between sediment plume dynamics and the continental island fringing reefs at which the coral colonies sampled were located.

Chapter 6 introduces the analyses of the massive corals sampled in Rockingham Bay. Locations of the coral colonies sampled and methods of sample extraction and pre-treatment are described. The relationship between stream flow in the Tully catchment and the UV fluorescence record in Rockingham Bay corals is then investigated to ascertain its characteristics and suitability in the context of the study objective.

Analysis of the sediment inclusions in the corals is reported in Chapter 7. Preliminary analyses of the sediment inclusions in Rockingham Bay coral skeletal material were undertaken in order to ascertain whether they were present and whether they were associated with terrigenous sources, and to identify a suitable analytical technique for undertaking large numbers of trace inclusion determinations on continuous coral skeletal samples. The proton-induced X-ray emission (PIXE) and proton-induced gamma emission (PIGME) techniques were selected. The results of these analyses, and their limitations, are described with respect to prospects of reconstructing a history of both sediment yield and nutrient yield in massive coral skeletal material.

Chapter 8 summarises the main findings of the research and outlines the conclusion reached with respect to the research objective.

<u>*Summary:*</u> The research plan implemented in order to achieve the stated research objective can be summarised as follows:

(i) Document the relevant characteristics of the study area.

(ii) Document short-term spatial and temporal variation in suspended sediment concentrations in the study catchment.

(iii) Reconstruct an annual sediment yield time series by space-time substitution based on the results of (ii), and correct for climatic variation using results from (i).

(iv) In the context of (iii), document the fate of suspended sediments in Rockingham Bay, with particular attention to the coral sampling sites.

(v) Analyse the relevant coral inclusion time series (ie. skeletal fluorescence and sediment inclusions).

(vi) Evaluate the relevant data from preceding chapters in the context of the research objective and draw a conclusion.

CHAPTER TWO

DESCRIPTION OF THE STUDY AREA

CONTENTS

2.1	TERRESTRIAL PHYSIOGRAPHY
2.2	MARINE PHYSIOGRAPHY
2.3	LAND USE
2.4	SUMMARY

2.1 TERRESTRIAL PHYSIOGRAPHY:

2.1.1 Geology, geomorphology and soils:

The geology and geomorphology of the study catchment are relevant to the objectives of this investigation in a number of important ways. Firstly, within the study catchment there is a strong relationship between patterns of land use and the lithology, topography and soils. Secondly, pedogenic processes applied to particular rock types, under a given climatic regime, lead to the development of soils with varying susceptibility to erosion under both natural conditions and changed land use. Thirdly, the tectonic history of the catchment affects natural rates of soil erosion and sediment yield. This section outlines the geology, geomorphology and soils of the study catchment in the context of these relationships.

The Tully River catchment lies at the southern end of the Hodgkinson Basin, defined to the west by the Palmerville Fault which lies a little west of the catchment's western boundary. The oldest rocks in this southern part of the Hodgkinson Basin are the Barnard Metamorphics which outcrop along the coastline north of the Hull River. To their west, forming the northeastern catchment boundary are the Barron River Metamorphics. Although Bryan (1925) suggested the Barnard Metamorphics were older, de Keyser (1964) proposed that differences between them were due to the higher grade metamorphism to which the Barron River Metamorphics had been exposed. He ascribed a middle Palaeozoic age. The Barron River Metamorphics' high grade metamorphism may be attributed to intrusion of Palaeozoic granitoids to shallow depths (Arnold and Fawckner, 1980).

During the late Palaeozoic, volcanism and plutonism were widespread throughout eastern Australia (Oversby, Black and Sheraton, 1980) and most of the rocks outcropping in the Tully River formed at this time. The Glen Gordon volcanics overlie the Barron River Metamorphics and outcrop along the Kooroomool Range, on the southern side of the Tully gorge, and form the southeastern boundary of the Evelyn Plateau. Late Palaeozoic granites intruded the Barron River Metamorphics and Glen Gordon Volcanics, and today form most of the northern and western catchment boundaries, and the southern part of the Evelyn Plateau (Fig. 2.1.1).

More recently, volcanism has been widespread in eastern Australia during the Cenozoic. Of the twelve volcanic provinces identified in northeastern Australia, nine are Plio-Pleistocene in age (Stephenson, Griffin and Sutherland, 1980). The northwest of the Tully catchment lies within the Plio-Pleistocene Atherton Province. Within an area of 1 800 km^2, in excess of 50 vents are known including cinder cones, lava shields, maars and a diatreme (Stephenson *et al.*, 1980). Of greatest relevance in the Tully catchment is a small volcano about 1 km south of Maalan (Stephenson *et al.*, 1980) from which lava flowed down Cochable Creek and into the Tully Gorge. The contact between the underlying channel sediments and this lava flow is elevated above the present stream channel, suggesting the possibility of eruption at a time of higher sea level or of uplift since that eruption.

From the vicinity of Koolmoon Creek to where the gorge widens into the lower gorge reach (c. AMTD = 70 km) the present Tully River largely flows along the contact between the basalt and the Glen Gordon Volcanics. There appear to have been successive lava flows.

The northeast Queensland coastline is backed by a more or less continuous scarp with elevations locally exceeding 1 000 m. The scarp is generally aligned NNW - SSE with the regional structural trend. However, between Tully and Cairns, in the areas of highest rainfall and a causal factor in that high rainfall, the trend of the scarp is North - South. In this region, residual or fault block ranges and hills (Coventry *et al.*, 1980) are aligned with the regional structural trend. The general pattern is for elevations of these residual landforms to decrease toward the coastline, with outlying hills surrounded by Quaternary alluvium. Further east, outliers occur as nearshore continental islands. The regional maximum elevation, at Mt Bartle Frere in the Bellenden Ker Range (1 611 m), is attained in one of these residual ranges. West of the scarp, elevations decrease gradually to the westward. Drainage from the west of the scarp is either westward toward the Gulf of Carpentaria (eg. Mitchell River draining the southern Atherton Tableland), or eastward to the coast through deep gorges (eg. Barron, Tully and Herbert), many of which have probably had their origin in zones of weakness along contacts between the resistant granite and other lithologies.

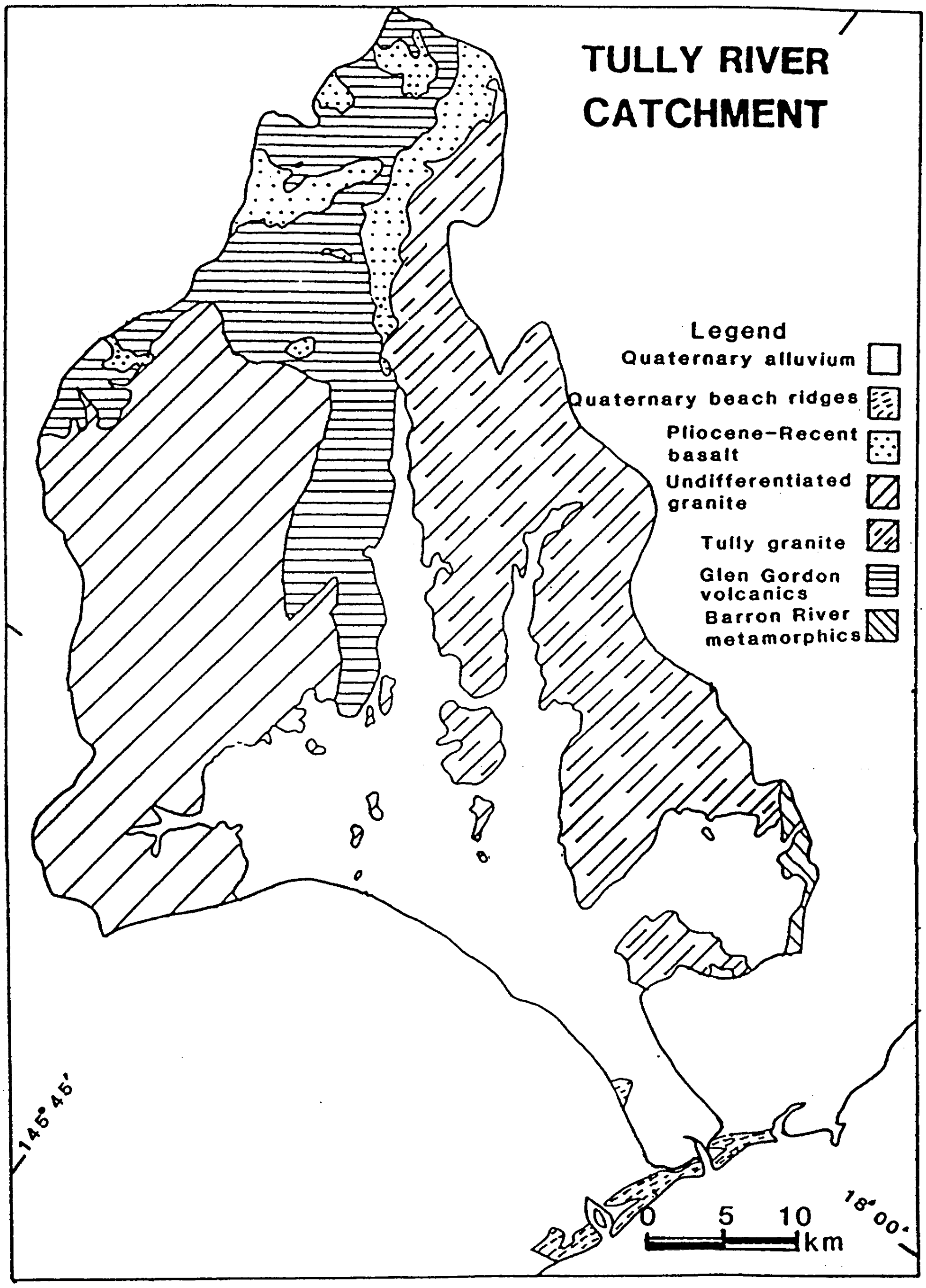


Fig. 2.1.1
Surficial geology of the Tully River catchment.

The origin of these coastal scarps has been the subject of debate for most of this century, a debate which was reviewed by Coventry *et al.*, (1980) and Hopley (1982). Three hypotheses have been advanced:-

i. The coastal escarpment was formed by late-Tertiary faulting of the subdued, duricrusted Tertiary landscape.

ii. Differential erosion formed the scarp, opinion varying between differential erosion as the major causal factor and differential erosion merely accentuating the effects of faulting.

iii. Scarp development occurred through successive episodes of flexure, resulting in the development of uplands and coastal subsidence. Scarp steepness was maintained by retreat through the Quaternary.

Marks (1925; 13) commented that ".. two out of three views must be wrong and not improbably the third". On the other hand, Hopley (1982; 29) suggested that "... It is probable that all three mechanisms are involved in the formation of the physiography of eastern Queensland ...".

The time of development of the escarpment has also been the subject of some discussion and revision. A Plio-Pleistocene age was suggested (Andrews, 1910) for the major tectonic events affecting eastern Australia. Alternatively, pre-Pliocene (Ollier, 1978), with the last major event in the Oligocene, was suggested by Wellman (1974). Wellman (1987) suggests that a mid-Cretaceous (c. 95 Ma) uplift initiation is most likely for the eastern Australian highlands, occurring at a time of changed tectonic and sedimentation patterns (Jones and Veevers, 1983). Most of the tectonic uplift (about two-thirds) had occurred by the mid-Cainozoic (Wellman, 1987). Wellman (1987) also notes that the uplift history is still not well understood. Most of the relevant work has taken place in the Southeast Highlands, and it must be kept in mind that uplift and erosion histories cannot be assumed to have followed the same course throughout the Eastern Highlands (Ollier, 1986).

Of most relevance to this study is recent instability. Two lines of evidence suggest that this is possible. Firstly, although the Tasman geosyncline region is considered stable, earthquakes do occur. The Tully River catchment lies within the Northeastern Queensland earthquake source zone of Gaull, Michael-Leiba and Rynn (1990). Their results suggest that an earthquake of intensity 5 (Modified Mercalli scale) has a 10% exceedance probability in a 50 year period in this zone. Secondly, if volcanic activity is assumed synchronous with uplift (Ollier, 1986), then regional tectonic activity is indicated from the Pliocene and possibly to the Holocene, given the available dates from the Atherton volcanic province (Stephenson *et al.*, 1980). Wyatt (1972) suggested that uplift may still be occurring.

More recently, Willmott and Stephenson (1989) have emphasised the role of differential erosion in the westward retreat of a scarp established by the formation of the Queensland Trough in the late Cretaceous. In their interpretation there has been no significant uplift since the late Cretaceous in a landscape dominated by westward scarp retreat. Elevation west of the scarp has been maintained by resistant granitic rocks and low rates of surface lowering in low gradient catchments.

The terrestrial part of the study area can be divided into four physiographic regions:-

(i) A plateau of 260 km^2 west of Cardwell Range and south of Tully Falls.

(ii) Several parallel ranges aligned NW-SE with the structural trend.

(iii) Depositional landforms of the alluvial and coastal plains.

(iv) Offshore islands.

2.1.1.1 The Plateau:

The Plateau area is bounded to the east by the Cardwell Range and to the west by the ill-defined Kirrama Range, which forms the drainage divide between plateau streams flowing to the coast via the Tully River and tributaries of the upper Herbert River (Fig. 2.1.2). Plateau elevation ranges between 700 and 900 m AHD. Drainage from the plateau is northward, with stream lines roughly aligned with the structural trend. The mean gradient of the plateau is c. 1:90. With the exception of a small area of Glen Gordon Volcanics at its western margin, the plateau lies almost entirely on granites. The plateau area was added to that of the Tully catchment by stream capture (Willmott and Stephenson, 1989).

2.1.1.2 The Ranges:

The major topographic features of the Tully catchment are the ranges aligned with the regional structural trend. From west to east these are the Kirrama, Cardwell, Tabletop and Walter Hill Ranges, all of which are granitic except the east face of the Cardwell Range in the Tully Gorge (Glen Gordon Volcanics) and the eastern end of the Walter Hill Range (Barron River Metamorphics).

On the eastern side of the plateau, the Cardwell Range has an elevation locally exceeding 950 m, about 900 m above the Tully flood plain. Along the south bank of the Tully Gorge the scarp is developed in the Glen Gordon Volcanics, with a slope of about 1:3, although locally it is much steeper. Further south, where the scarp is developed in granite, slopes are similar, although slope profiles differ in that the crest of ranges in granite tends to be domed, whereas in volcanics it is much sharper. A number of granitic, residual hills outcrop from the south bank floodplain alluvium.

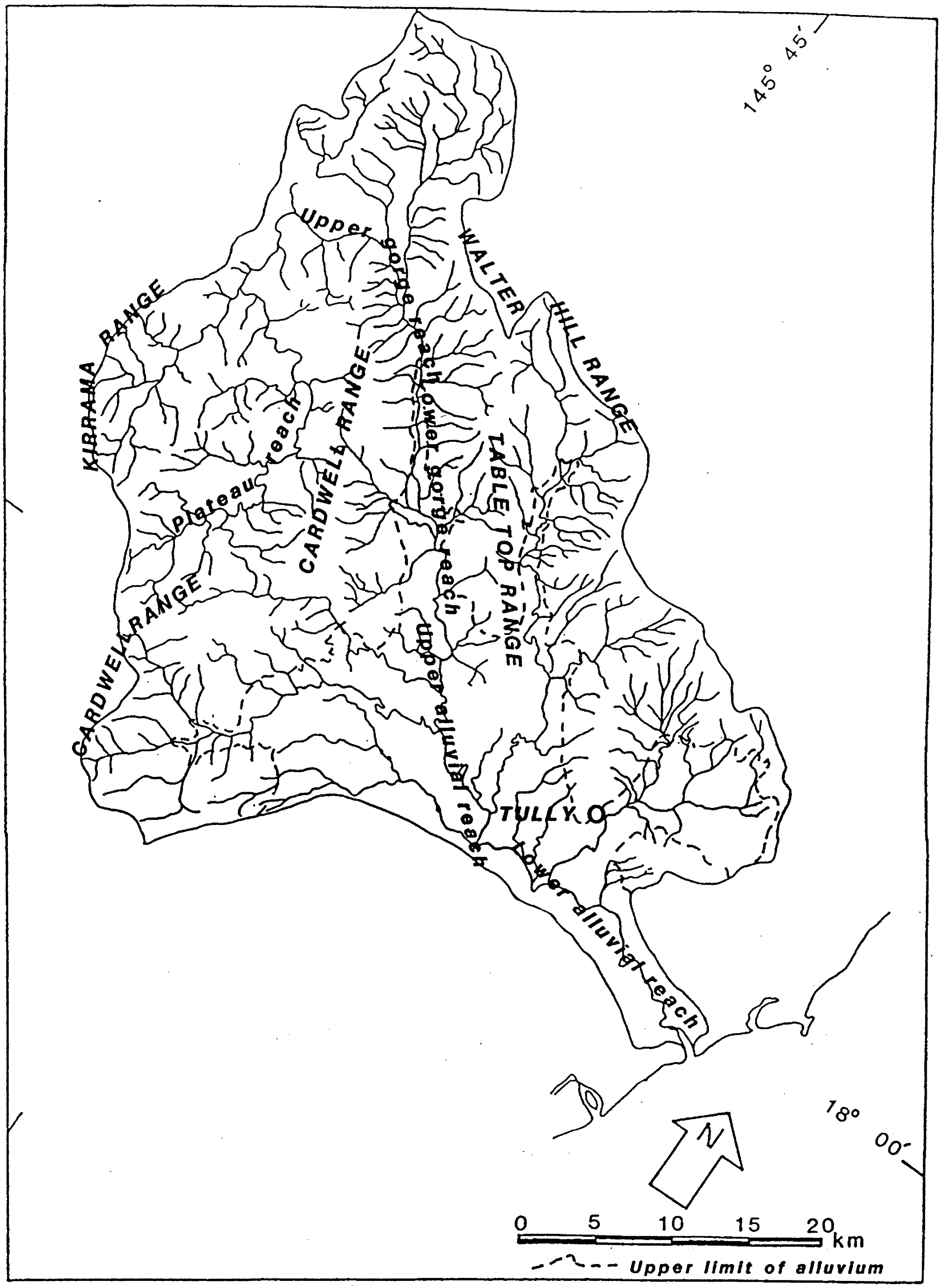


Fig. 2.1.2
Physiography of the Tully River catchment.

The east side of the Tully Gorge is formed in granite by the Table Top range which, like the Cardwell Range, locally exceeds 900 m. Elevation decreases to the southeast, where this range forms a series of residual hills separating the Tully River and Jarra Creek drainage lines. Slopes along the north bank of the Tully Gorge are generally c. 1:5.

The Tully Gorge probably formed along the contact between the Glen Gordon Volcanics in the southwest and the Tully granite in the northeast. Subsequent to the lava flow down the alignment of Cochable Creek, downcutting along the Tully River appears to have occurred in the Glen Gordon Volcanics, along the contact with the Atherton Basalt. The Jarra Creek drainage line has incised within the Tully granite and, like the Tully Gorge, the slopes on its southern bank are steeper (c. 1:3) than on the flanks of the Walter Hill Range to the north (c. 1:5). The Walter Hill Range forms the northern boundary of the Tully catchment. The true structural alignment of this range is with the regional trend, terminating in the vicinity of Mt Tyson (658 m) and forming the drainage divide between the Jarra and Banyan Creek subcatchments. The slope on the northeast of this range is c. 1:3.

The crest of the Walter Hill range, where it lies in granite, falls within the elevation range of the plateau. Where it lies in the less resistant Barron River Metamorphics, however, it is of much lower elevation, generally < 350 m. This is the case where these rocks form the northern boundary of the Banyan Creek catchment, along a separate alignment, also parallel to the regional trend.

2.1.1.3 Depositional landforms of the alluvial and coastal plains:

About 28 % of the area of the Tully catchment, and 62 % of the adjacent Murray catchment, is Quaternary alluvium and colluvium.

Numerous alluvial fans extend from the slopes of the Cardwell and Tabletop Ranges toward the Tully River. The topographic evidence suggests that, in some cases, the distal ends of these fans have been truncated by the river, although the stratigraphic evidence is unclear. The fans are generally inactive and incised, with slopes of c. 10 %. Hopley, Harvey and Pye (1980) suggest that the most likely periods of fan aggradation on the northeast Queensland coastal plain are Kershaw's (1980) period 10 and periods 4 and 5, roughly equivalent to oxygen isotope stages 5b - 5d and to the last glacial maximum, respectively. Cannon, Smith and Murtha (1992) have described an extensive, uniformly sloping (< 2 %) landform (interpreted as a 'sheet flood fan' using the nomenclature of McDonald, Isbell, Speight, Walker and

Hopkins (1990) extending up to 15 km northeastward from the base of the Kirrama Range, in the area to the south of Davidson Creek.

Alluvial plains occupy extensive areas of the Tully and major tributary catchments, reaching a maximum width of 20 km across the shared floodplain of the Tully, Murray and Hull Rivers inland of the oldest beach ridge sequence. Air photo interpretation and ground survey indicate numerous features of a geomorphically active floodplain (abandoned channels, cutoff meanders etc.), although these are conspicuously absent in some areas (notably the lower Banyan Creek). Aspects of these features are discussed in greater detail below.

Channel morphology and drainage diversions: The Tully River channel can be subdivided into a number of morphological zones, largely consistent with the physiographic regions discussed above (Fig. 2.1.3). The plateau reach flows northwest along the strike in a broad valley (c. 10 km wide) with a relief of about 80 m. The mean gradient in this reach is 1:450 and the sinuosity is 'irregular' (1.86) according to the classification of Schumm (1963). This reach of the Tully flows on granite, as does the parallel flowing Nitchiga Creek immediately to the west. By comparison, sinuosity in Nitchiga Creek is only 1.12.

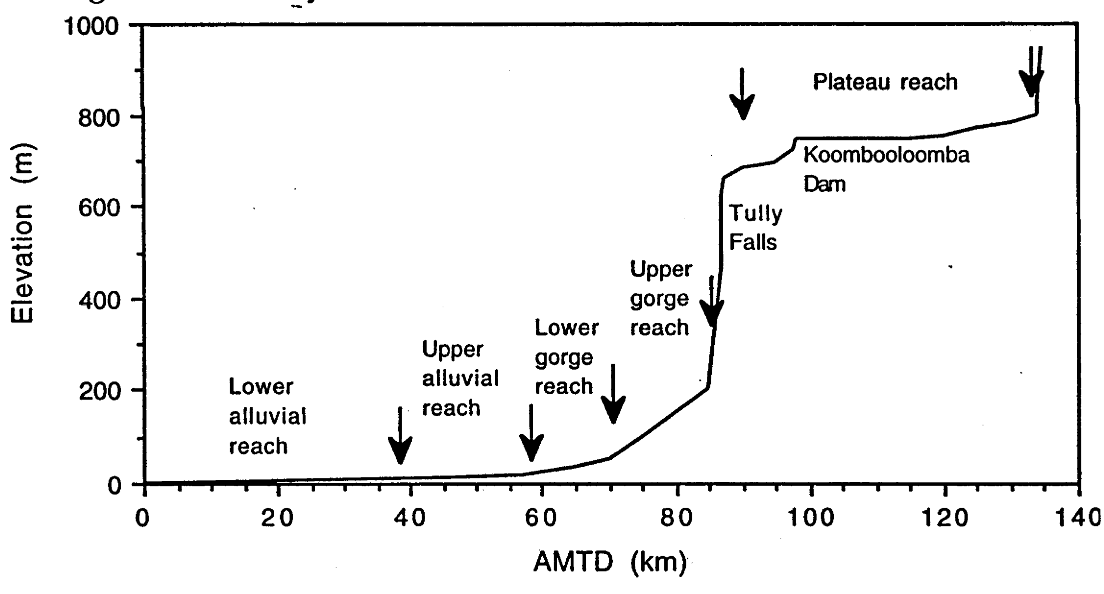


Fig. 2.1.3
Long profile of the Tully River showing major morphological zones. (Adopted Middle Thread Distance (AMTD) is as mapped by Queensland Water Resources Commission; elevation from 1:50 000 and 1:25 000 topographic sheets).

The Tully River descends the escarpment about 87 km upstream at the Tully Falls. The narrow upper gorge reach has a steep gradient (1:100) with transitional sinuosity (1.25), cutting across the structural trend in an easterly direction. In this reach, basalt flows from the Atherton Province have entered the Tully River channel. In the lower gorge reach the channel is aligned with the structural trend, the valley widens (to about 8.5 km) and the gradient decreases markedly (1:430). Sinuosity is 1.26, similar to that of the upper gorge, and relief remains high (c. 900 m).

Downstream from AMTD (Adopted Middle Thread Distance) = 55 km, the valley widens considerably into a broad alluvial plain. The upper and lower reaches of the Tully River within this plain are morphologically distinct. The upper alluvial reach is structurally aligned, has a gradient of 1:1 200 and transitional sinuosity (1.21). Extrapolation downstream aligns this reach with Bedford Creek and the Murray River mouth. Three of the four largest tributaries enter the Tully River in this reach. By contrast, the lower alluvial reach, about 40 km long, does not conform to the structural trend, flowing in a generally easterly direction. It has a more gentle gradient (1:4 500) and a much higher sinuosity (1.60) than the upper alluvial reach. The lower 40 km of the Murray River channel, with a similar gradient and much lower discharge, has a 'tortuous' sinuosity of 1.94.

Evidence of drainage diversions is widespread in the north Queensland coastal landscape. Causes of these diversions have been the subject of debate. For example, the southward diversion of the Mulgrave River from Trinity Inlet to Mutchero Inlet has been attributed to damming by basalt flows (de Keyser and Lucas, 1968), tectonism (Bird, 1970) and sedimentation (Willmott and Stephenson, 1989). Drainage diversion due to channel aggradation is often associated with sea level fluctuations. Elsewhere on the coastal plain drainage diversion due to aggradation and sea level oscillations is documented for the Bohle-Ross and Alice-Black river systems (Hopley and Murtha, 1975). Examination of air photos and topographic maps suggests that this also applies to the Liverpool-Maria Creek, South Johnstone-Moresby River, Liverpool Creek-Moresby River and the Herbert River-Trebonne Creek-Palm Creek systems.

In the Tully River catchment there is also evidence of drainage diversions which are of relevance to this study. In describing these, it is emphasised that no stratigraphic evidence is presented in support of the conclusions drawn.

Firstly, it seems likely that Banyan Creek has, prior to historical records and probably during the Holocene, flowed north of Mt Mackay and into the Hull River estuary. The evidence in support of this suggestion is as follows:-

- The morphology of the Hull River estuary suggests formation by a much larger stream than presently uses it.
- As pointed out above, many of the regional drainage lines are aligned with the structural trend and have incised along the contact between differing

rock types. Incision of the palaeo-Banyan Creek probably took place along the contact between the Tully Granite of Mt Mackay and the Barron River Metamorphics of the Walter Hill Range. Drainage in the Banyan catchment is generally concordant with such a drainage pattern until it is intercepted by Little Banyan Creek which flows NE-SW toward the new drainage between Mt Mackay and Mt Tyson (Fig. 2.1.4).

- Other tributaries to the Tully River have complex morphologies in their lower reaches. Scroll bars, cutoff meanders, abandoned channels and other such features are numerous. In the case of lower Banyan Creek, however, there are no such geomorphic features. There is a single channel, deeply incised with no evidence of abandoned channels or channel migration.

Although the channel morphology suggests that this diversion is recent, it predates historical maps (earliest 1884) which show the Banyan confluence with the Tully at the present location. The most likely cause of this diversion is probably choking of the stream channel by fan deposits on the northeast slopes of Mt Mackay. However, the likely age of active fan aggradation ($\geq$ last glacial maximum) is not consistent with the channel morphology of the lower Banyan Creek. Morphology of lower Banyan Creek suggests a very recent incision of that channel.

The second drainage diversion of interest is that of the Tully River. It is postulated that, during the Holocene, the Tully River discharged to Rockingham Bay through the Murray River estuary. The evidence supporting this assertion is as follows:-

- The Murray estuary morphology suggests formation by a much larger river.
- Meander wavelengths in Bedford Creek, through which the Tully would have flowed to reach the Murray mouth, are consistent with those of the present lower Tully River, and not with those of the present Murray River, suggesting that the channel was formed by the former rather than the latter (Fig. 2.1.4).
- There is little evidence of channel change in the lower reaches of the Tully River, whereas there is ample evidence of numerous changes upstream of the Banyan Creek confluence.
- The present Murray and Tully River channels are connected by a drainage line (Weiss Creek) which appears to be a drainage ditch. Inspection of the earliest maps and vertical air photos shows that it is actually a natural channel. Although at the present time it flows to the Tully by way of a cutoff (artificially) meander bend, close inspection of the air photos shows that the abandoned channel of Weiss Creek is visible along the eastern edge of the meander loop and that it meets the Tully River 500 m downstream of its

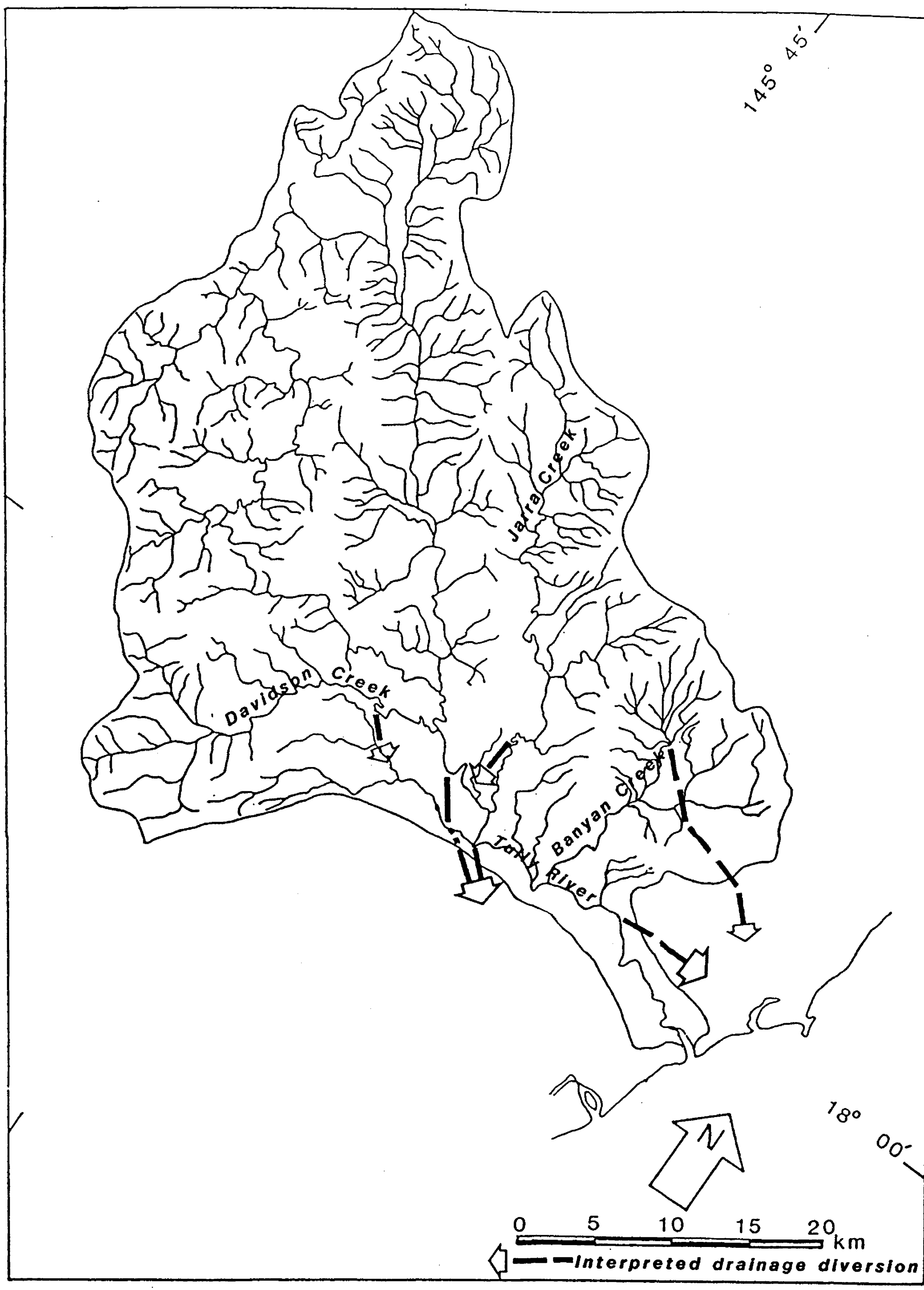


Fig. 2.1.4
Interpreted drainage diversions on the Tully River floodplain.

confluence with Banyan Creek. It is clear that Banyan Creek formerly met the Murray River at the position of the present confluence of Weiss Creek and the Murray River, ie. Weiss Creek was the lower reaches of Banyan Creek. In order for this to occur the confluence of the Tully and Murray Rivers must have been upstream of the Weiss Creek confluence (Fig. 2.1.4).

It also seems possible that the Tully River may have used the Hull River estuary, although floodplain and channel morphologies suggest that this is probably confined to acting as a distributary during flood discharges. Other drainage diversions interpreted as occurring on the Tully River floodplain include those of Jarra and Davidson Creeks (Fig. 2.1.4).

Brizga (1992) has compared post-European settlement river channel morphological changes for north Queensland rivers (using historical maps and air photos) with pre-historic behaviour (as indicated by palaeochannels and other floodplain features). None of the north Queensland rivers investigated (Tully, Herbert, Haughton, Burdekin, Don and Proserpine) appeared to have undergone any major morphological changes since settlement, in contrast with the two rivers (Thompson and Avon) investigated in Victoria.

Observations in the course of this study support this conclusion for the Tully River catchment. There are at present three cutoff meanders in the Tully River at c. 20, 33 and 52 km AMTD. That at 52 km is mapped as cut off on the earliest map on which this reach is clearly depicted (1927). (Historical maps referred to in this section are parish maps (Parish of Tyson, County of Cardwell) published by the Survey Office, Dept. of Public Lands, Brisbane). That at 33 km is shown as the river course on all maps prior to and including one published in December, 1929, but is cut off on the September, 1932 map. With the exception of limited logging and even more limited logging on the plateau, there was no land use intensification upstream of this reach prior to this time. As previously mentioned, that at 20 km AMTD (adjacent to the Banyan Creek confluence) was cut off artificially.

Similar stability during the historical period is exhibited by the major tributaries. Comparison between modern maps and the earliest map depicting the lower reaches of Echo and Davidson Creeks, published in 1929, shows that there has been no change in course of these streams since that time, although there is considerable evidence of palaeochannels in their vicinity. Jarra Creek presently follows the same course as depicted on the September, 1932 map. On earlier maps the lower 6 km of this stream is depicted as an essentially straight channel. This appears to be a mapping error as there is no evidence in the floodplain morphology of this stream to suggest that such a course had previously existed. It may be significant that the reach which is apparently incorrectly mapped lies within a single cadastral unit. As previously mentioned, there is no evidence of changed channel morphology in the lower Banyan, either pre-historical or historical.

There is no evidence of historical channel change in the Murray River between 15 and 65 km AMTD. Minor changes between 13 and 15 km AMTD may be attributed to inaccuracy of the early maps. Air photo evidence shows that a meander cutoff has occurred between 5 and 10 km AMTD.

In addition to the major bi-directional spillage between the Tully and Murray via Weiss Creek, an additional six uni-directional spillages from the Tully to the Murray have been identified (Anon., 1987). Of these, three occur between the Banyan and Jarra Creek confluences with the Tully, and three between the Jarra and Davidson Creek confluences with the Tully.

In summary, evidence from the Tully River and its major tributaries, and the Murray River indicates that little channel change has taken place which could be considered a geomorphic response to land use intensification.

<u>Beach ridges:</u> Beach ridge sequences are typical of segments of the northeast Queensland coastline exposed to the prevailing southeasterly and easterly winds. Ridge sequences are generally composed of quartz sand, have an elevation of up to 5 m and are usually less than 400 m wide (Coventry *et al.*, 1980), although there are many examples of sequences of much greater width.

The coastline of Rockingham Bay is backed by a series of quartz sand beach ridges which widens northward from the vicinity of Cardwell. The outer, Holocene sequence attains a maximum width of 1.5 km between the Tully and Hull Rivers. An auger hole through the inner most ridge of this sequence revealed a well developed podzol soil profile with an A horizon 0.6 m thick, a B horizon to 1.4 m and a C horizon overlying mangrove muds at 2.5 m. The observed profile development is consistent with that of the Kaygaroo soil series (Murtha, 1986) occurring in the outer sequence between the Johnstone and Tully Rivers. Seaward of this site, younger ridges have soils exhibiting progressively less soil development.

In some localities, remnants of an inner sequence, probably of Late Pleistocene age, exist. In the Cairns hinterland, inner ridge remnants are presumed to date to the last inter-glacial (Willmott and Stephenson, 1989). Similarly, west of the Mourilyan Sands beach ridge sequence, a small, indistinct remnant exists (Murtha, 1986), possibly of the same age. At Cowley Beach, south of Innisfail, a multiple barrier system c. 11 km wide occurs, the most conspicuous feature of which is a 3 km wide sequence of red quartz sand ridges from 8 to 11 km inland (the Mourilyan Sands). Murtha (1986) maps the soils of the inner ridge sequence near the Hull River in the same soil series (Brosnan series) as the Mourilyan sands, classified as Red Earths. However, the inner sequence at Rockingham Bay is morphologically and pedologically distinct from the Mourilyan sands, having more subdued relief and much closer spacing between ridges. Although Murtha (1986) maps this inner sequence at Rockingham Bay as the same soil series as at Cowley Beach, he describes a rudimentary podzol profile from this ridge sequence on the north bank of the Hull River (Googarra series) with an A horizon of 0.6 - 0.8 m thick, and a B horizon to a depth of 0.8 - 1.2+ m. This profile is consistent with that observed in an auger hole drilled in the this ridge sequence south of the Tully River. The A horizon thickness at this site (observed in a cutting) varied from 1.0 - 1.2 m, the B horizon was developed to a depth of c. 1.8 m and the thickness of this ridge was > 6.2 m (the water table was intersected at 5.0 m).

The maximum width of the Rockingham Bay sequence is 7 km at the Hull River. Remnants of the inner sequence are about 2.5 km wide and there is an intervening area of alluvium 3 km wide. Apart from differences in soil development and sharpness of relief, and their wide separation, the much greater age of the inner sequence than the outer sequence is evident from the greater destruction of the inner sequence by lateral movement of stream channels. The extent of the destruction of the inner sequence north of the Tully River could be interpreted as indicating that avulsion took place prior to formation of the outer ridge sequence. It also suggests that sediments from reworked beach ridges provide a significant source of sands for incorporation into the bedload of the Tully River in its lower reaches (<10 km AMTD).

Although the beach ridge sequences of the Rockingham Bay coastline occupy about 35 km^2 of the lower Hull, Tully and Murray catchments, only a very small proportion of them is used for agriculture and their infiltration rates are sufficiently high that no significant runoff from them would reach Rockingham Bay. Detailed mapping of the Quaternary coastal deposits between Townsville and Cairns is provided by Holmes, Stephens, Jones and Searle (1991).

Soils: Soils of the Tully/Murray Basin are described in detail by Murtha (1986), Murtha and Cannon (1992) and Cannon, Smith and Murtha (1992). The study area soils may be divided into three major classes:- those of the littoral landforms bordering Rockingham Bay (principally mangrove muds and beach ridges and swales); those either *in situ* or developed on colluvial and alluvial fan deposits, predominantly in association with acid igneous

(Tully granite and Glen Gordon volcanics) rocks; and those of the extensive alluvial deposits of the Tully/Murray floodplains. As pointed out above, the soils of the littoral landforms have little relevance to this study and will not be further discussed here. A generalised soils map of the Tully/Murray basin is given in Fig. 2.1.5.

Within the Tully/Murray basin there are only very limited areas of soils developed in association with basalts and metamorphics. Cannon *et al.* (1992) point out that, because of the strong lithological similarities between the Tully granite and the Glen Gordon volcanics, the soils developed on them have very similar morphologies. The fine-grained nature of the volcanics is not evident in the overlying soils. They also point out that discrimination of soils on *in situ* saprolite and those on transported material is difficult and somewhat subjective because of similarities of the strongly-weathered underlying materials, a difficulty confirmed during fieldwork for this study by the inconclusive results of drilling numerous auger holes in the lower gorge area of the Tully catchment.

The general pattern of soil distribution on acid igneous parent materials is of well-drained red earths on the upper slopes grading to relatively poorly-drained, coarse-grained gradational and duplex soils on the lower slopes (Cannon *et al.*, 1992). Soils on upper slopes (*Utchee* series; Fig. 2.1.6) have dark, reddish-brown A horizons (0.08 - 0.40 m thick) of sandy, light clay. Moderately to strongly structured B horizons may reach to a depth of 2.0 m. On the upper slopes of fans, *Tyson* and *Hillview* series are gradational to uniform, with red sandy clay loam A horizons and clay loam B horizons, to a depth of about 2.0 m. Natural vegetation of *Tyson* and *Hillview* series was rainforest and dry sclerophyll, respectively. *Tyson* series predominates in these slope positions in the Tully catchment, with *Hillview* common in the Murray and smaller catchments to the south. *Thorpe* series, on mid-fan slopes, is a yellow earth with sandy loam A horizons < 0.5 m, thick, and B horizons (sandy clay loam to medium clay) of 0.5 to > 2.0 m depth. On lower slopes of fans, soil series recognised include *Prior* and *Lugger*, the former under predominantly *Eucalyptus*, *Melaleuca* and *Casuarina* natural vegetation and the latter under *Melaleuca*. These soils have massive to weak structures, textures ranging from sandy clay loam to medium heavy clay and, like other alluvial fan soils, have fine gravel throughout. A horizons range from 0.1 to 0.35 m thick with B horizons from 0.75 to > 2.0 m depth (Cannon, *et al.*, 1992).

Erodibility of soils in the study area was mapped by Smith *et al.* (in prep.) on an eight point scale (0 - 7) of increasing erodibility, based on both the intrinsic soil properties and the slopes on which each soil type is developed.

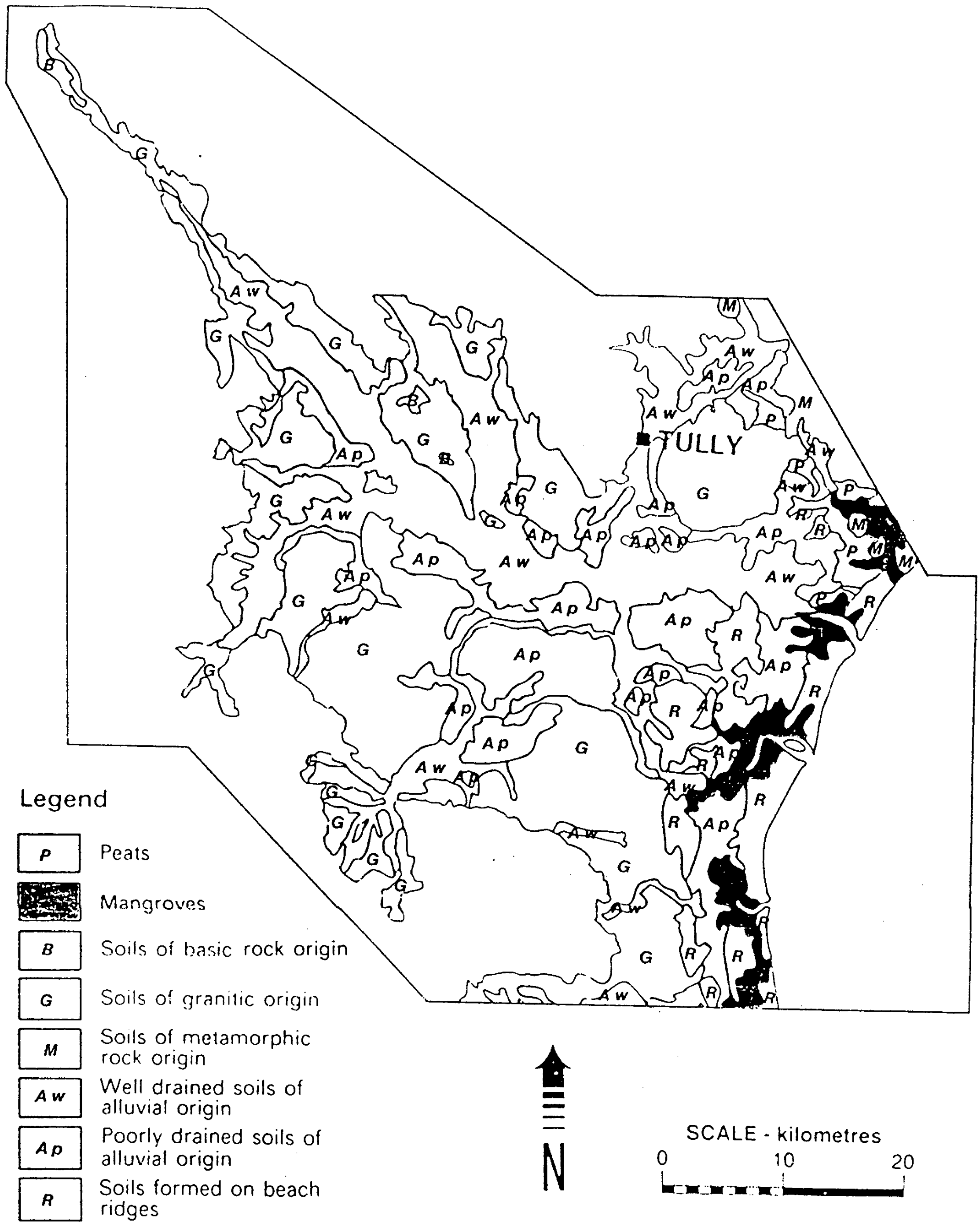


Fig. 2.1.5
Generalised soils map of the Tully-Murray lowlands (based on Cannon *et al.*, 1992 and Murtha, 1986).

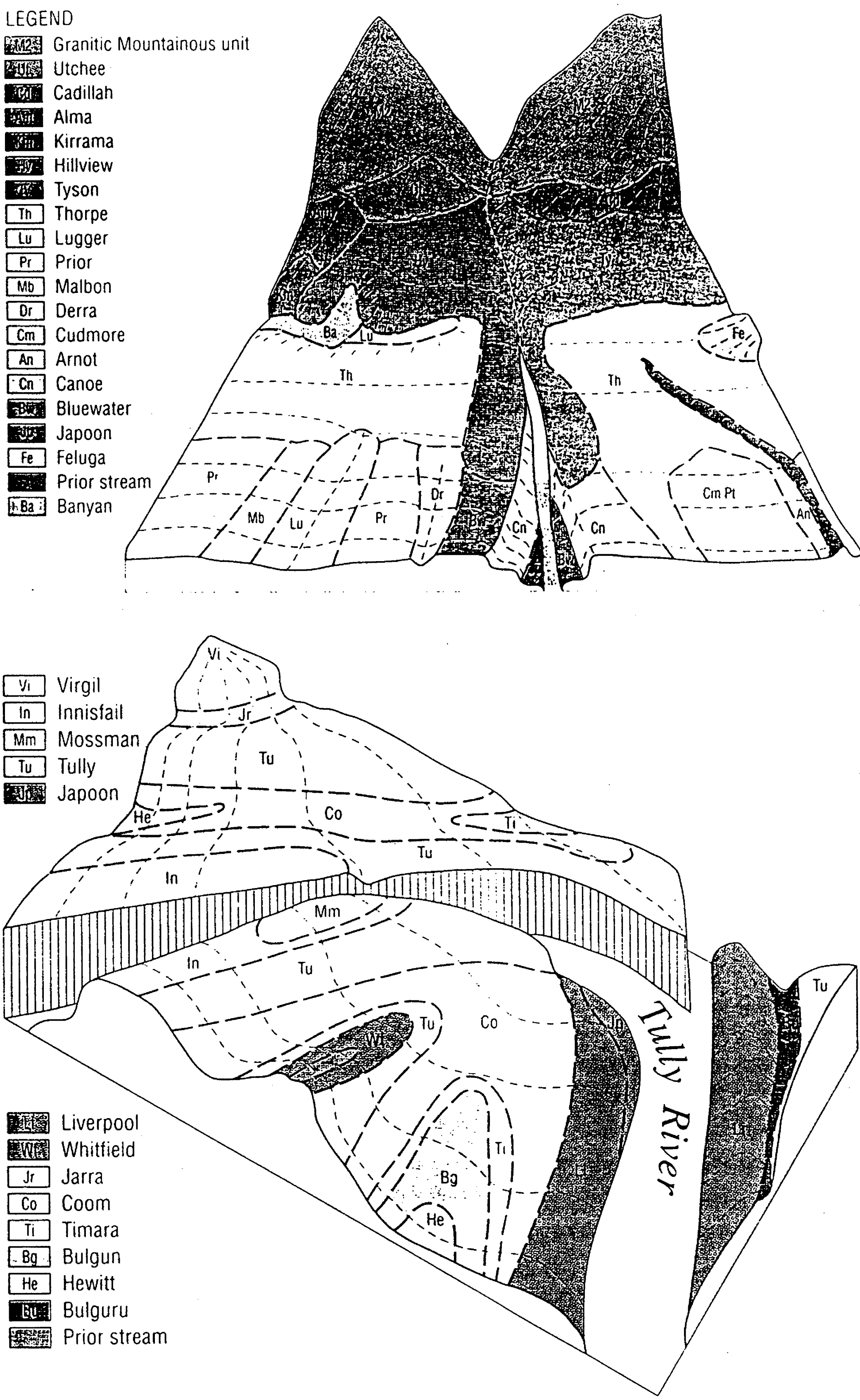


Fig. 2.1.6
Schematic diagram illustrating the relationship between soils and topography in the Tully-Murray basin (from Cannon *et al.*, 1992)

On this scale *Utchee* series soils are generally allocated a ranking of 5 - 6. *Tyson* and *Hillview* soils on the upper fan slopes have soil erodibility rankings in the range 2 - 6, the higher erodibility occurring on the steeper slopes. *Thorpe* series, on mid-fan slopes, has soil erodibility from class 0 to 2. Soils on the lower slopes (*Prior* and *Lugger*) lie in classes 0 - 2. Soils on metamorphics (east side of Banyan Creek catchment) are classified as erodibility classes 4 - 6, and the limited area on basalts in the Cochable Creek valley is of low erodibility (class 0).

Land suitability in the study area is mapped in 10 classes (Smith *et al.* , in prep.) briefly described in Table 2.1.1. *Utchee, Tyson* and *Hillview* soils are generally of classes A5 and B1, unsuitable for production of crops such as sugar cane and bananas. Mid-fan slope soils are classified as A5 on steeper slopes and A2 on the lower slopes. *Prior* and *Lugger* soils on the lower fan slopes are generally in the A3 land suitability class (sugar cane and improved pasture).

Class	Land use suitability
A1	Sugarcane, bananas, pawpaws and improved pasture.
A2	Sugarcane, bananas and improved pasture.
A3	Sugarcane and improved pasture.
A4	Bananas and improved pasture.
A5	Adapted tree crops and improved pasture.
A6	Adapted dry season annual crops and improved pasture.
B1	Improved pasture, marginal for tree crops.
B2	Improved pasture, marginal for dry season annual crops.
C	Improved pasture.
D	Non-agricultural lands.

Table 2.1.1
Land suitability classes in the Tully - Murray basin
(from Smith *et al.* , in prep.).

Well-drained soils of the alluvial plain are predominantly red earths in higher areas, grading through yellow earths to alluvial soils in lower areas (Cannon, *et al.,* 1992). The *Innisfail* series is typical of soils on the upper floodplain and on stream levees, and is the predominant soil type on alluvium in the lower gorge reach of the Tully River. These soils are brown, strongly structured, with a uniform to gradational profile form. A horizons (generally 0.15 but up to 0.25 m thick) have a silty loam to light clay structure. B horizons (to > 2 m deep) are generally silty light clay to medium heavy clay. *Tully* series also develops on floodplains and on stream levees, at lower elevations than *Innisfail* series. These soils are yellow, strongly structured with a uniform to gradational profile, commonly with mottling at depth. Clay loam A1 horizons are generally < 0.15 m deep. Remnant natural vegetation on these soils and landforms is predominantly gallery rainforest. This soil type is common in the alluvium of the major tributary streams such as Banyan, Jarra, Davidson and Echo Creeks.

The *Liverpool* series is the predominant soil of the geomorphically active, lower channel benches of the Tully, Jarra, Davidson and Echo (Fig. 2.1.6), generally under remnant gallery rainforest vegetation. These soils have thin (< 0.15 m), sandy loam A horizons, and B horizons to depths in the range 0.10 to 1.2 m. *Liverpool* series soils do not occur in the lower reaches of Banyan Creek due to its morphological characteristics, as discussed above.

All of the soils of the coastal plain lie in the lowest erodibility class (0; Smith *et al.*, in prep.). Land suitability of the alluvial soils is quite variable. The extensive areas of *Innisfail, Tully* and *Liverpool* series soils are generally the best agricultural terrain, in suitability classes A1 and A2, with areas of *Liverpool* series in the A4 class, and B2 and C in the upper floodplain areas of Davidson, Echo and Barbed Wire Creeks.

Numerous other soil series, their topographic position illustrated in Fig. 2.1.6, have been mapped in the Tully-Murray basin. Those described above are spatially dominant in the study area, and the relative areas depicted in Fig. 2.1.6 are not indicative of their areas on the ground.

Where drainage on the floodplain is poor, these soils are replaced by humic gleys. These soils occur predominantly in the lower reaches of the Tully and Murray Rivers, particularly between these rivers and to the south of the Murray. Soils in these areas are typically clay loams and clays, with dark, strongly organic A horizons which vary widely (eg. 0.03 - 0.7 m) in depth. Natural vegetation is predominantly *Eucalyptus, Melaleuca* and *Lophostomen*, with *Melaleuca* and sedgelands in the wetter areas (Cannon, *et al.*, 1992). These are soils of low erodibility (class 0) and land suitability class D and, in some areas, A3.

The greater part of the land cleared in the study area (land use is discussed in detail in Chapter 2.3) lies in the lowest soil erodibility class (class 0). However, a small area of land of higher erodibility has been cleared in both the Tully and Murray catchments (Fig. 2.1.7). In the Murray this is largely limited to relatively low erodibility classes (1,2), whereas in the Tully some land in high erodibility classes has been cleared (1.6 % and 0.4 % of the Tully and Murray catchments, respectively, in classes $\geq$ 4), predominantly for grazing rather than for cultivation. In the Banyan Creek subcatchment much larger areas in the higher erodibility classes have been cleared (6.4 % of the catchment in classes $\geq$ 4), generally for cultivation.

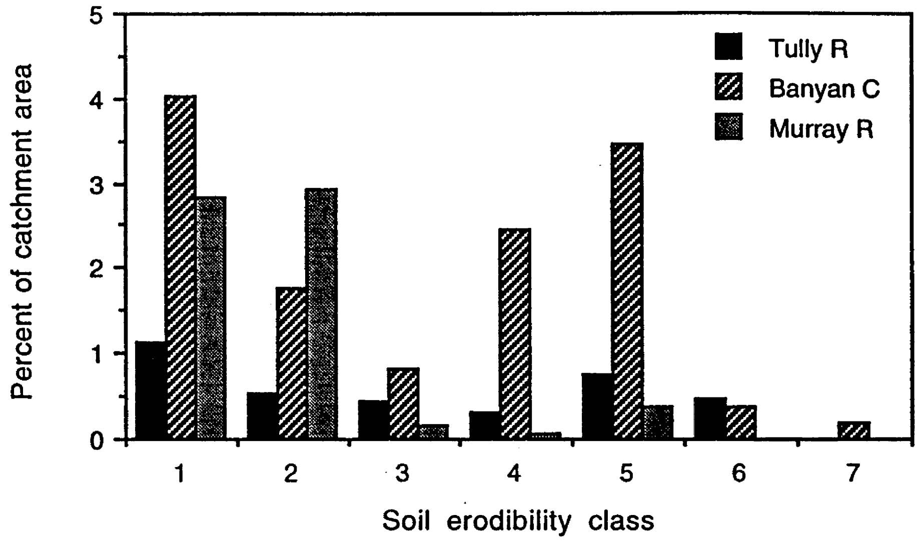


Fig. 2.1.7
Catchment areas cleared (%) of the Tully, Banyan and Murray catchments by Smith *et al.*'s soil erodibility classes ≥ 1 (catchment areas upstream of Euramo, Tully, and highway crossing, respectively; data from unpublished maps of Smith *et al.* (in prep.)).

2.1.1.4 Offshore islands:

The islands of Rockingham Bay are aligned with the regional structural trend, in two groups. In the north, the Family Group of islands, aligned along a SE - NW axis, generally decrease in area and elevation seaward, consistent with the topographic trend on the mainland ranges (Table 2.1.2). The largest island, Dunk, is composed of mid-Paleozoic metamorphics as are the small islands to its west (Kumboola, Timana). Lithology of the eastern half of Dunk Island and of the other islands in the Group is Tully Granite. To the southwest, Goold Island (also Tully Granite and Almaden Granite in the west) lies along the structural alignment from Mt Tyson to the north of Hinchinbrook Island (Cape Richards). Numerous small bay head beaches formed of Holocene, predominantly calcareous, sands occur around island margins. All except 4 of the 17 continental islands in Rockingham Bay have developed leeward sand spits. These sand spits are formed on fringing reef platforms (Hopley, 1968; 1971), their morphology determined by patterns of wave refraction in the absence of stabilising beach rock, unlike similar landforms in drier areas to the south (Hopley, 1971). Sediments are a mixture of terrigenous and calcareous, with a relatively high terrigenous proportion in the mid-Holocene and predominantly calcareous sediments in modern spit beaches. The terrigenous sediments are derived from reworking of regolith during the mid-Holocene transgression and from calcareous sediments from the adjacent fringing reef (Hopley, 1971). Kumboola Island is connected with Dunk Island by a rocky reef, which dries at low tide. A shallow reef, submerged at low tide, lies between Smith and Bowden Islands.

Both Dunk and Bedarra Islands have SE - NW aligned ridges along their northeast margins. Consequently, most runoff is to the southwest coasts of these islands, from catchments of ≤ 1 km^2 in the case of Dunk Island and smaller on Bedarra. Smaller islands of the Family Group are roughly concentric topographically, with runoff evenly distributed around their coastlines. Several very small islets in Rockingham Bay are largely irrelevant to this study, being little more than emergent rocks.

Island	Area (km^2)	Elevation (m)	Lithology	Distance from coast on structural trend	Distance and True bearing from Tully River mouth
Dunk	6.6	270	Metamorphics (W) Granites (E)	7.5	14.4; 047
Kumboola	0.05	61	Metamorphics	7.0	12.2; 047
Timana	0.13	79	Metamorphics	6.5	10.0; 059
Bedarra	0.80	107	Granites	5.5	10.3; 075
Wheeler	0.26	86	Granites	9.0	11.9; 088
Coomb	0.36	110	Granites	10.5	13.4; 095
Smith	0.03	64	Granites	12.5	15.5; 092
Bowden	0.03	61	Granites	12.5	15.2; 095
Hudson	0.17	82	Granites	13.5	15.9; 098
Brook	0.84	76	Granites	26.0	26.9; 117
Goold	8.4	408	Granites	19.0	19.4; 140

Table 2.1.2
Structural characteristics of the main islands of Rockingham Bay.

2.1.2 Climate:

The aspects of the regional climate dealt with in this section focus on temperature and rainfall (in the context of vegetation dynamics), wind climate (as it interacts with topography to determine rainfall distribution and quantity) and rainfall (in the context of soil erosion, runoff and stream flow).

2.1.2.1 *Rainfall:*

The study area lies in the *Af* climatic region according to Koppen's system (humid tropical; moist with no cool season and no distinct dry season; mean rainfall in the driest month > 60 mm (Dick, 1975)). The most significant climatic feature of the study area is the very high, and strongly seasonal, rainfall. Gentilli's (1986) phytohydroxeric index indicates a regional growing season longer than six months and a regional climate capable of supporting rainforest vegetation. The general atmospheric circulation in the wet tropics region generates three major rainfall producing mechanisms (Bonell *et al.*, 1986). The first of these is influenced by the position of the maximum cloud zone, situated equator-ward of the monsoon trough. The position of the trough during summer is normally at 13° - 14° S. Rainfall over the wet tropics (17° - 18.5° S) is produced by more southerly excursions of the trough or, more importantly, by the development of vortices which occur as tropical depressions or cyclones. These systems produce large volumes of intermittent summer rainfall. The second mechanism produces year round rainfall and is a consequence of low pressure troughs embedded in the circumpolar upper westerlies. The third rainfall producing mechanism is the Hadley cell return flow which oscillates as high pressure systems, and associated high pressure surface ridges along the east coast, move eastward across the Tasman Sea.

There is strong orographic control on rainfall along the Queensland coast, with both the orientation and elevation of the coastal ranges influencing precipitation patterns. In spite of the general trend of the Queensland coastline from SSE to NNW and the similar regional structural trend, as a result of the local pattern of scarp retreat the topographic trend between 17 - 18.5°S is aligned south to north. Coastal range elevations are also at their highest in this region. These factors combine to produce the highest rainfalls in Australia, with isohyetal gradients closely matching the topography (Bonell, 1988).

Mean annual rainfall at Tully (Stn. 032042, 1925 - 1991 (n=67)) is 4 188 mm which is comparable with other lowland stations in the region. The range is from 2 489 (1961) to 7 899 mm (1950) (Fig. 2.1.8). The coefficient of variation is 24% and the standard deviation 1 008 mm. The time series suggests a relatively dry period during the 1950s and 1960s and a wet period in the 1970s.

The topographic effect on rainfall can be deduced from the data for the Bellenden Ker Range (Fig. 2.1.9). Interpolation from these data suggests that mean annual rainfall on topographic prominences in the Tully catchment (eg. Mt. Tyson, Mt. Mackay) is likely to be of the order of 6 000 - 6 500 mm,

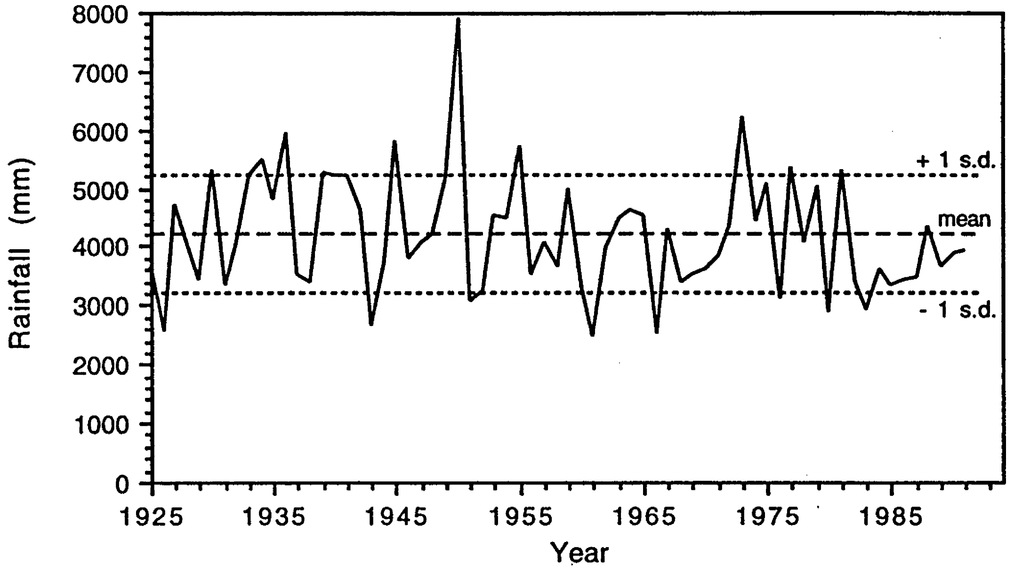


Fig. 2.1.8
Time series of annual rainfall at Tully (Stn. 032042) for the period 1925 - 1991 showing mean and standard deviation of the annual series.

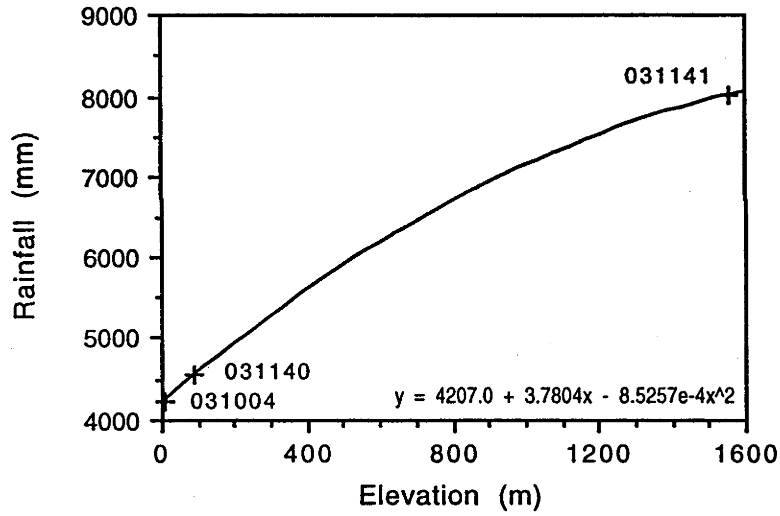


Fig. 2.1.9
Relationship between rainfall and elevation derived from stations at Babinda (031004), Bellenden Ker Bottom Station (031140) and Bellenden Ker Top Station (031141) (1974-1991).

and possibly > 7 000 mm in the headwaters of the Banyan Creek catchment. Cardstone, 60 km inland, receives 2 660 $mm.yr^{-1}$ and rainfall at Ravenshoe on the Evelyn Plateau is 1 245 $mm.yr^{-1}$. Coastal stations in the south of Rockingham Bay have relatively low precipitation rates, in spite of the close proximity to the coast of the Cardwell Range, due to the rainshadow effect from Hinchinbrook Island which reaches an elevation of 1 112 m. Cardwell, for example, has a mean rainfall of 2 132 $mm.yr^{-1}$. Rainfall on the

Tully/Murray floodplain ranges from 2 300 (Upper Murray area) to 3 000 (Euramo area) $mm.yr^{-1}$.

On the larger offshore islands close to the coast, rainfalls are similar to those on the adjacent mainland. At Dunk Island rainfall is 3 058 $mm.yr^{-1}$ (1973-1986) and at Bedarra, 2 766 $mm.yr^{-1}$ (1971-1975). Rainfall at the outer islands (eg. Coomb, Hudson, Brook) is likely to be considerably lower.

Rainfall is highly seasonal, due largely to the influence of the monsoon trough and tropical low pressure systems. At both Tully and Cardstone, 52 % of rainfall occurs in 25 % of the year (January - March; Fig. 2.1.10). In each of these months, however, the rainfall exhibits high interannual variability with monthly rainfall at Tully in the range 19 - 2003 mm, 139 - 1667 mm and 281 - 1907 mm for January, February and March, respectively.

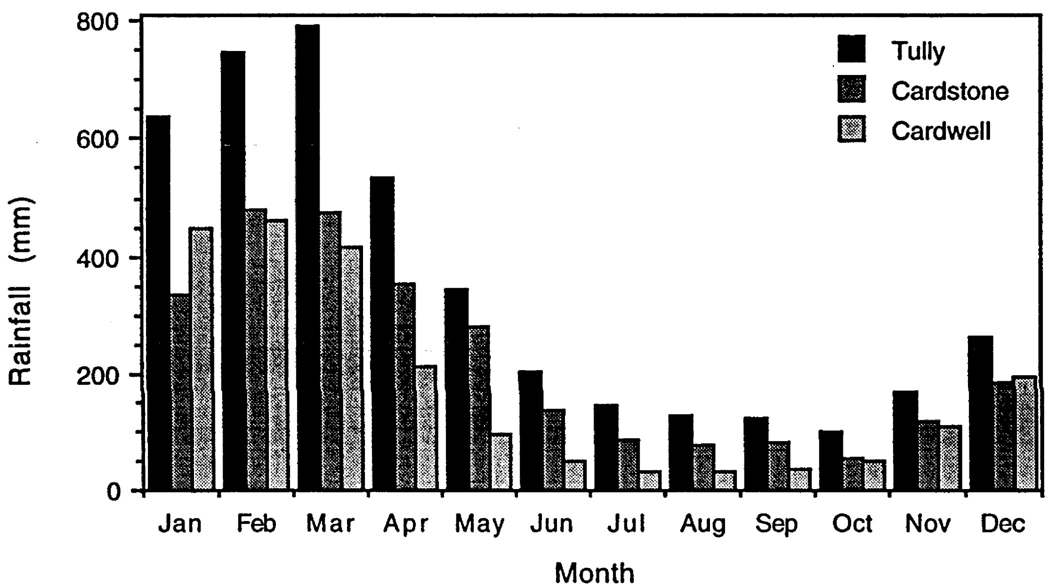


Fig. 2.1.10
Seasonal rainfall pattern at Tully (1925 - 1991; Stn. 032042), Cardstone (1971 - 1991; 031115); and Cardwell (1871 - 1991; 032004).

Throughout the lowland and montane areas of the catchment and the offshore islands, January - March totals are generally in the range 50 - 55 % of the annual total. For drier plateau stations (eg. Ravenshoe, Kirrama) seasonality is stronger with 60 - 65 % of the annual total falling in these three months. There is also a change in the nature of the seasonal variation associated with the total rainfall. At dry stations December rainfalls are greater than post-monsoon April rainfalls, whereas at high rainfall stations the April totals are higher than those in December (Fig. 2.1.11).

Bonell (1988), analysing rainfall records for experimental catchments near Babinda, described a number of rainfall characteristics which are relevant throughout the region. Because rainfall during the monsoon season generally occurs in pulses of varying intensity, rather than continuously or consistently, rainfall on just a few days can contribute a large percentage of

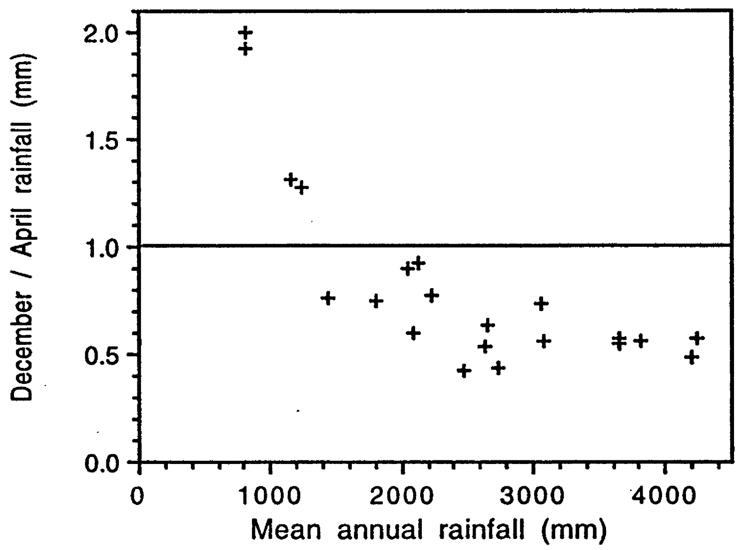


Fig. 2.1.11
Variation in the ratio of pre- and post- monsoon rainfall in relation to mean annual rainfall (Stations from 15.5 - 18.5 °S).

the annual total and a large percentage of the annual total may occur on consecutive days. For example, 1 327 mm fell at Tully in the three days 10 - 12.3.1927, 28 % of the total for that year. Rainfall during the monsoon season is the major factor determining the annual total, but can be highly variable from year to year. Nevertheless, even during a very dry monsoon season, large volumes of rainfall can still occur in a single event. During the "post-monsoon season" (April to mid-June; Bonell and Gilmour, 1980) rainfalls are generally lower than in the preceding months. However, large volume events may still occur with daily totals > 100 mm. This is indicated by maximum monthly rainfalls at Tully of 1586 mm and 806 mm in April and June, respectively. There have been four days in the period 1925 - 1990 when 24 hr rainfall at Tully exceeded 250 $mm.dy^{-1}$ during April. The period June to November is the dry season during which rainfall from the trade-wind stream is the dominant influence. Intermittent heavy rains may still occur due to the passage of upper level westerly troughs (Bonell, 1988).

As a result of high rainfalls occurring seasonally in intermittent pulses, rainfall intensities in the region are also high. Bonell (1988) has identified four rainfall intensity seasons, as follows:

Summer monsoon	(December to March)	70 - 170 $mm.hr^{-1}$
Post - monsoon	(April to mid-June)	25 - 80 $mm.hr^{-1}$
Winter	(mid-June to September)	gen. < 20 $mm.hr^{-1}$
Pre - monsoon	(October - November)	< 110 $mm.hr^{-1}$

Intensities cited by Bonell (1988) are for maximum 6 - minute rainfall in major storms at a study site 5 km east of Babinda. Given that mean annual rainfall (1970-1977) at Bonell's gauging site (4 239 mm) is 95 % of that at Tully for the same period, it seems likely that similar intensities will apply in the Tully area.

Recurrence intervals for daily rainfalls at Tully (1925 - 1990) are shown in Fig. 2.1.12. The 10 year daily rainfall at Tully (480 mm) compares with 720 mm and 1020 mm at the Bellenden Ker bottom and top stations (Herwitz, 1982), respectively, indicating the influence of topography on rainfall intensity as well as annual totals. The highest 24 hr rainfall recorded at Tully is 606 mm, compared with a maximum recorded in the wet tropics of northeast Queensland of 1 140 at Mt Bellenden Ker (Top station).

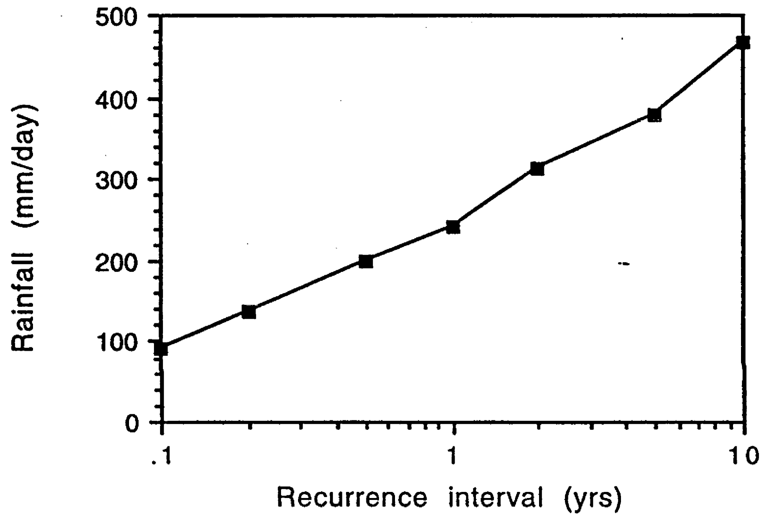


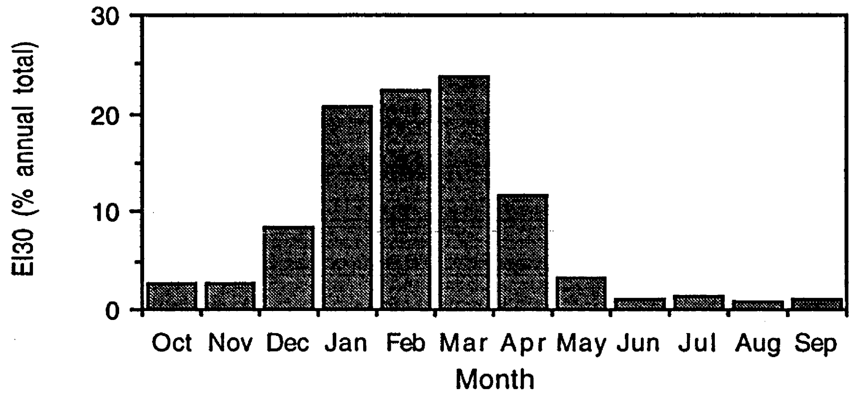
Fig. 2.1.12
Recurrence interval of daily rainfalls at Tully (1925 - 1990).

2.1.2.2 Rainfall erosivity:

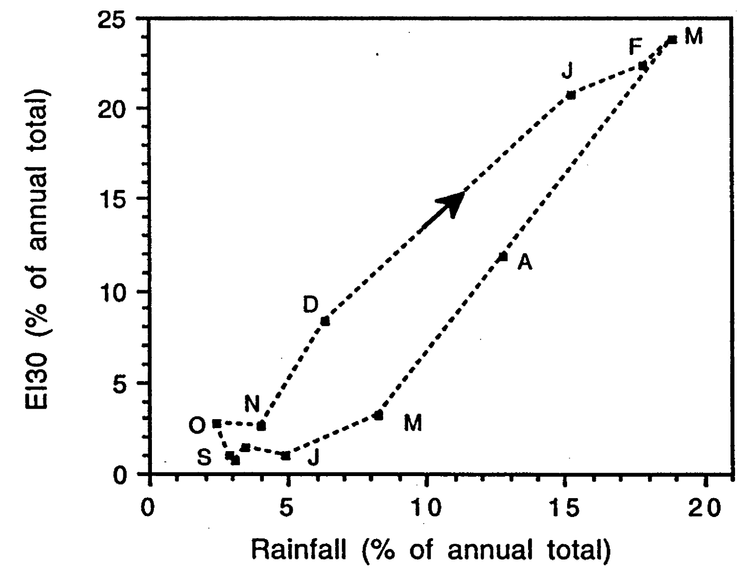
In simple terms:

Erosion = *f* (Erosivity, Erodibility) (Selby, 1982) and the erosivity of rainfall is a function of its energy. Analyses of the relationship between rainfall and erosion for different terrain types has shown that the measure of rainfall erosivity best correlated with erosion rates varies spatially. Erosivity indices proposed include: EI_{30} (the product of kinetic energy and maximum 30 minute rainfall intensity during a storm (Wischmeier *et al.*, 1958)), KE>25 (the kinetic energy of all rainfall above a threshold of 25 mm (Hudson, 1971)), and AI_m. (the product of storm rainfall and its maximum 7.5 minute intensity (Lal, 1976). The EI_{30} has been widely adopted as a measure of rainfall erosivity in association with use of the Universal Soil

Loss Equation (USLE), discussed further in Chapter 4. Rosenthal and White (1980) mapped the distribution of the EI_{30} in Queensland and their results for Koombooloomba, in the upper Tully catchment, show that there is a strong seasonal pattern in rainfall erosivity (Fig. 2.1.13a) with rainfall erosivity concentrated in the January - March period. The intra-annual distribution of rainfall erosivity is strongly hysteretic, with high erosivity in relation to discharge in the months of December and January, and relatively low erosivity in April and May (Fig. 2.1.13b). The hysteretic nature of the rainfall/rainfall erosivity relationship in the Tully catchment is generally consistent with the seasonal pattern identified by Bonell (1988).



(a)



(b)

Fig. 2.1.13
Monthly rainfall erosivity index (EI_{30}) as a percentage of the annual total at Koombooloomba (a); Hysteretic relationship between rainfall and rainfall erosivity (b). Tully rainfall (032042); Koombooloomba rainfall erosivity (EI_{30}) (data from Rosenthal and White, 1980; EI_{30} = product of total storm rainfall energy and the maximum 30-minute intensity).

However, long term trends in rainfall and, more importantly, rainfall erosivity, are of particular relevance to studies of the interaction of land use and sediment yield. Because there are no long term pluviograph records for the region it is not possible to compute EI30 values for the period during which land use intensification has occurred. Therefore, long term variation in rainfall erosivity can only be assessed by analysis of the daily data.

Several approaches to the estimation of long term patterns of high intensity, high erosivity rainfall have been used. For example, although rainfall and rainfall intensity (rainfall.rain day^{-1}) in eastern Australia are generally correlated in space and time, analysis of their relationship for a number of regions in Australia shows that significant deviations do occur through time (Neil and Brierley, 1990; Neil and Yu, 1991, 1994; Yu and Neil, 1991; 1993a). Times of anomalously high intensity are expected to be times of high erosion potential.

Neil and Brierley (1990) used monthly rainfall.rain day^{-1} data to show that a decreasing trend in high intensity rainfall, in relation to the annual total rainfall, had occurred over the last century at a number of stations in the north Queensland wet tropics. The Tully high intensity rainfall, over a shorter period, followed the same general trend.

Yu and Neil (1991) assessed temporal changes in rainfall erosivity in southeastern Australia using daily data. They used a threshold below which erosion would infrequently occur, based on regional runoff plot data, and estimated the erosivity of rainfall above that threshold, following the results of Ekern (1954) and Smith and Wischmeier (1957) which showed that erosivity is a power function of intensity. The exponent generally lies in the range 1.6 - 2.2 (Meyer, 1981) for a wide range of cropping conditions and soil types and including both splash and runoff erosion. Yu and Neil (1991 and subsequently) used an exponent of 2.0. Limitations of this approach include changes in the parameter values with differing antecedent conditions for each event, variation in rainfall duration within the 24 hour period, spatial variation in soil erodibility and natural ground cover, and long term changes in the threshold value as land use changes. Nevertheless, this approach gives some indication of the temporal changes in the rainfall component of the erosion process.

A similar approach is based on the work of Richardson *et al.* (1983) who showed that a good estimate of EI30 could be obtained from daily data using a relationship of the form:

$$EI30 = aP^b$$

where P = the rainfall amount, and a and b are equation parameters.

For 11 sites in the USA east of the Rocky Mountains with between 4 and 17 years of record, the exponent varied between 1.59 and 1.99 ($\bar{x}$ = 1.81). Although errors were large for individual events, good estimates of the annual total and seasonal distribution of EI_{30} were obtained. Elsenbeer *et al.* (1993) evaluated the Richardson *et al.* model for a tropical site in western Amazonia using 2.5 years of pluviograph data. The exponent of 1.64 lies within the range reported by Richardson *et al.* (1983) and the prediction of EI_{30} using b = 1.64 was not significantly different from that using b = 1.81. The Richardson *et al.* power function model is generally consistent with the earlier work of Meyer (1981) and has also been confirmed by several workers in North America (eg. Haith and Merrill, 1987; Bullock *et al.*, 1989; Selker *et al.*, 1990).

Analysis of the Tully rainfall record was carried out using the following formula to compute the rainfall erosivity index (EI) for each water year:

$$EI = 0 \quad \text{when } i \leq i_o; \text{ otherwise } \quad \Sigma(i - i_o)^2$$

where: i = rainfall intensity ($mm.day^{-1}$)
i_o = threshold intensity ($mm.day^{-1}$)
(Yu and Neil, 1991)

In other words, the threshold value is subtracted from each daily rainfall total (if the rainfall exceeds the threshold), the result is squared and these values are summed to calculate the erosivity index (EI) for the year. The general validity of this model is supported by a preliminary analysis of the relationship between the EI_{30} and daily rainfall at Cairns, north Queensland. The annual EI, calculated as daily rainfall squared above a 12 mm threshold, is significantly correlated with annual EI_{30} totals for 16 years of record (1957 - 1972) with $r^2 = 0.80$ (Yu and Neil, in prep. b; Cairns EI_{30} data supplied by K. Rosenthal). Given the strong relationship between Tully rainfall and Tully River stream flow (Chapter 3.4.4) and the absence of any other long term rainfall record in the catchment, the Tully rainfall at Station 032042 is assumed representative of the catchment.

The results of this analysis of Tully daily rainfall data reveals a decreasing trend in rainfall erosivity during the period of record (Fig. 2.1.14) which is not reflected in the annual rainfall totals (Fig. 2.1.8). The trend in rainfall erosivity is consistent with other stations in the northeast Queensland wet tropics (Yu and Neil, 1994), although it is most clear at Tully. Decreasing rainfall erosivity occurs in spite of a suggested increase in tropical cyclogenesis since the 1940s (Milton, 1974), although it should be stated that more recent analyses (Holland, 1981; Nicholls, 1985) indicate that the trend reported by Milton is probably a consequence of improving data quality.

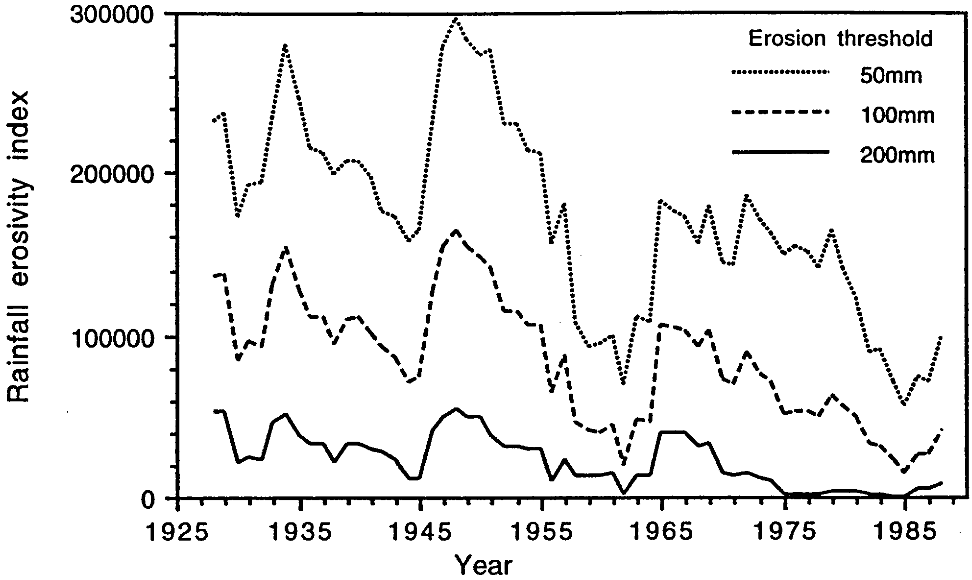


Fig. 2.1.14.
Time series (5 yr running mean) of rainfall erosivity index at Tully (Stn. 032042). (Exponent is 2.0; 100 mm threshold is assumed relevant to rainforest cover, 50 mm threshold to pasture cover; water years)

Fig. 2.1.15 shows the temporal distribution of extreme 24 hr rainfalls at Tully. The 50 highest rainfalls (recurrence interval > 1.3 years) should occur at a frequency of 3.8 per 5 year period if distributed evenly in time. The figure shows that neither the frequency of these events, nor the rainfall occurring in them is evenly distributed. In fact 68 % of these extreme events had occurred in the first 46 % of the time period. 62 % of these extreme events occurred during February and March, one occurred in October, two (4 %) in December, 12 (24 %) in January, and 8 % occurred in April.

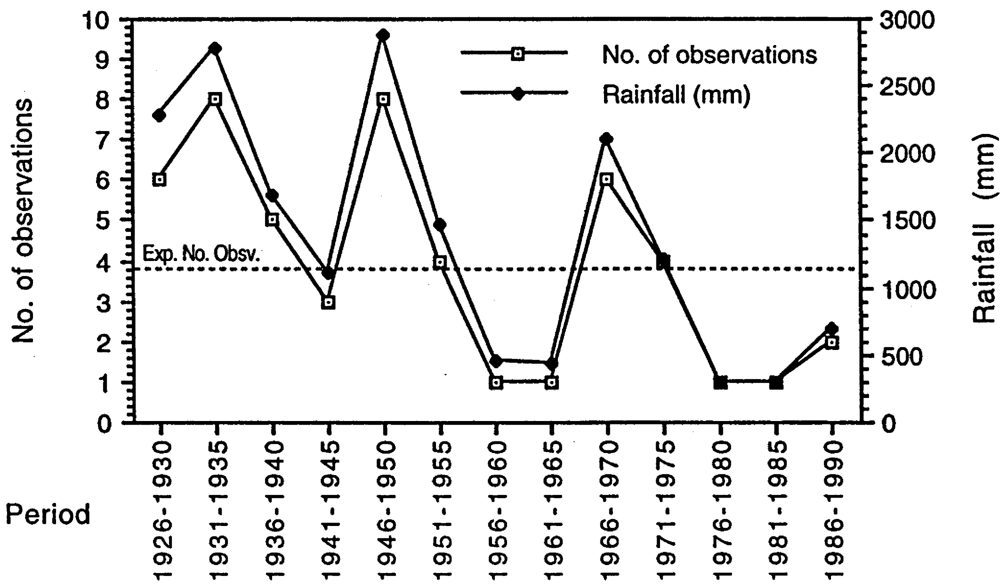


Fig. 2.1.15
Time series (5 yr increments) of frequency of occurrence of extreme 24 hour rainfalls at Tully, and of associated rainfall. The associated rainfall is the sum of the extreme 24 hr rainfalls occurring in a given 5 year period.

2.1.2.3 *Temperature:*

Seasonal variations in mean monthly minimum and maximum temperatures at Cardwell are shown in Fig. 2.1.16. This pattern is very similar to that for other coastal stations between Cardwell and Cairns. Mean daily maximum temperatures are in the range 31.0 to 32.0 °C for the months November to March, and never fall below 25°C. The seasonal pattern of minimum temperatures is consistent with that for maximums, although the range is greater. July is the coldest month. Seasonal variation of sea surface temperature is discussed in 2.2.3.

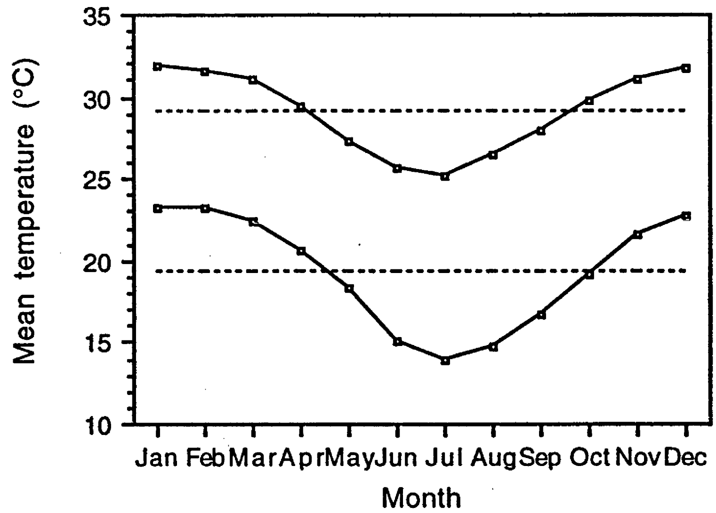
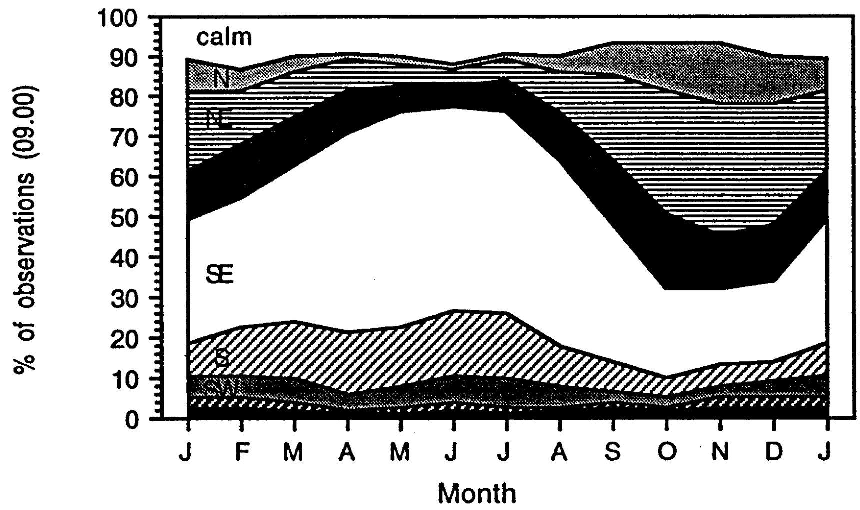


Fig. 2.1.16
Monthly means of daily maximum and minimum temperatures at Cardwell (Stn. 032004; 34 years of record) and annual means.

2.1.2.4 *Wind climate:*

The general regional climatic patterns, discussed previously, result in a predominance of the southeast tradewind during winter months and a greater frequency of northwesterlies associated with southward movement of the monsoon trough in summer months. This pattern is most evident over the northern GBR and Cape York peninsula. At 18^{o} S there is relatively little influence from the northwesterly and the wind climate is dominated by onshore winds, particularly southeasterlies. Proportional graphs of wind observations at Cardwell, based on 34 years of record (1957 - 1991), illustrate the general pattern (Fig. 2.1.17). The 9 am observations are more representative of the regional wind pattern because the sea breeze is of greater significance than the land breeze (Oliver, 1978; Hopley, 1982).



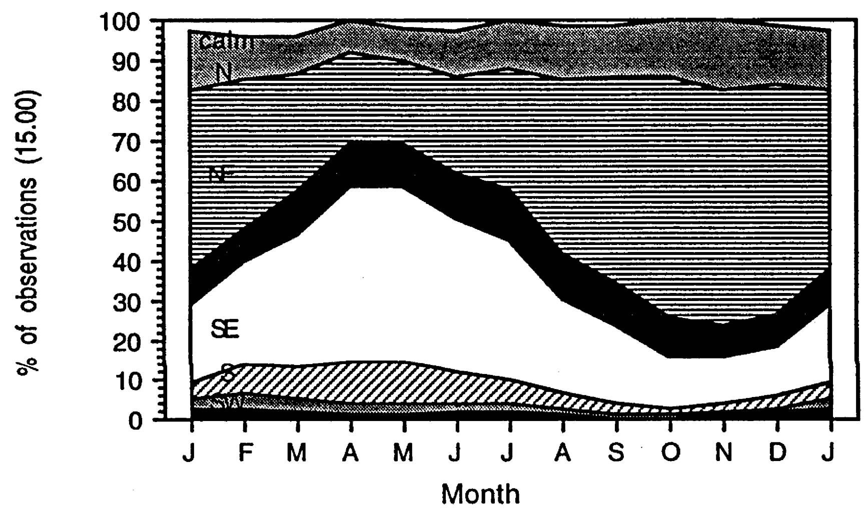


Fig. 2.1.17
Seasonal variation in wind direction at 09.00 and 15.00 at Cardwell (Aust. Bur. Met. data).

In the context of this study, the wind climate is relevant to the terrestrial physiography in two main ways. Firstly, seasonal variations in the wind regime result in seasonal contrasts in atmospheric accession and, secondly, extreme wind events, such as cyclones, can result in destruction of vegetation. Onshore wind energies are greatest during the late dry period (September - November), prior to the onset of the wet season, and at their lowest during the wet season months of February, March and April and in May (Fig. 2.1.18). The potential for onshore transport of salts is therefore greatest during the pre-wet season months.

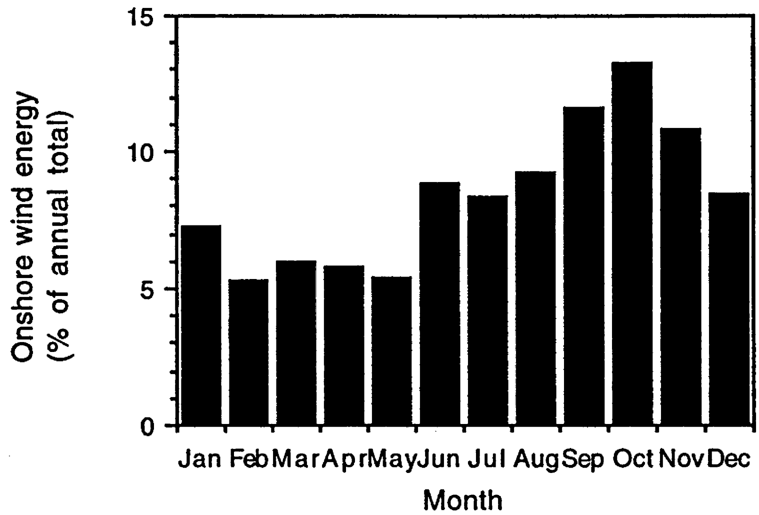


Fig. 2.1.18
Monthly variation in onshore wind energy at Cardwell (calculated as velocity^3 of winds from NE, E and SE).

Although on average the maximum mean monthly wind energies occur during the pre-monsoon period, extreme wind energies occur in association with cyclones, generally between December and April, and predominantly between January and March (Hopley, 1982). These events have the capacity to cause widespread forest destruction (often at a time of high intensity rainfall) and subsequently result in increased fire frequency (Webb, 1958; Unwin *et al.*, 1988). Both of these effects have the potential to increase stream sediment loads.

2.1.3 Hydrology:

The hydrological characteristics of the study catchment are relevant to this study in relation to both catchment processes and to sediment plume dynamics in the nearshore marine environment. The inter-annual and seasonal variability of stream flow are also relevant to the relationship between coral fluorescence and stream flow (Chapter 6.2) and the usefulness of this relationship for hindcasting hydrological conditions.

The catchments of the Tully, Murray and Hull Rivers occupy a total of 2 195 km^2. Of this area, 105 km^2 is in the Hull catchment of which only 10 km^2 is gauged. Only 155 km^2 of the 510 km^2 Murray River is gauged (30 %), and 1 475 km^2 (88 %) of the 1 685 km^2 Tully catchment. There are additional gauging stations upstream on the Tully River. Gauging on the Tully River at Euramo (Stn. 113006A) is by gas-electric transducer with Leupold-Stevens automatic recorder, commencing in 1972 and continued to date. That on the

Murray River at Upper Murray (Stn. 114001A) is also by gas-electric transducer with automatic recorder, from 1970 to date.

In spite of of the damming of 10 % of the catchment on the plateau, runoff from the Tully catchment is high, both in absolute terms and as a proportion of rainfall. At Koombooloomba, gauging the plateau area of the Tully catchment above 99.6 km AMTD, mean annual runoff (1949 - 1964) is 2 157 mm which is 83 % of the mean annual precipitation (Bonell, 1988). For the Tully River above Euramo (17.5 km AMTD) the mean annual runoff is 2 185 mm which is 74 % of the mean annual precipitation (Hausler, 1991). The mean annual rainfall for the Murray basin (including 630 km^2 of minor streams to the south of the Murray catchment proper) is lower than that for the Tully catchment (by 16 %). Mean annual runoff is 1 428 mm, only 57 % of the mean annual rainfall (Hausler, 1991). These figures represent approximations only as the Murray data is based on gauging of only 14 % of the basin, Bonell's runoff coefficient uses very different periods for catchment rainfall and runoff and the Tully and Murray River estimates are confounded by Weiss Creek which connects these streams below Upper Murray and above Euramo.

Inter-annual stream flow variability is largely a function of regional climate, particularly rainfall reliability. Inter-annual variability of both total runoff (Qt; c.v. = 33%) and of instantaneous maximum discharge (Qi; c.v. = 16%) is lower in the Tully catchment than in the other major coastal streams of Queensland (c.v. (Qt) = 40 - 119%; c.v. (Qi) = 49 - 141%; Fig. 2.1.19). Rivers included in the analysis are the Pascoe, Normanby, Daintree, Barron, North Johnstone, Tully, Herbert, Haughton, Burdekin, Don, Pioneer, Fitzroy, Calliope and Burnett. It is striking that the coefficient of variation for instantaneous maximum discharges in the Tully (16 %) is one-third that of the Pascoe (second lowest in this data set) and is very similar to equatorial rivers such as the Sepik and Ramu in which the coefficients of variation for instantaneous maximum discharges are 12 and 13 %, respectively.

Equatorial streams with high-rainfall catchments are known to have low variability of flow. For example, Pickup (1984) showed that the 100yr recurrence interval flood was only twice the magnitude of the 2yr flood in the Fly and Purari River basins in southern Papua New Guinea. The Ramu (equatorial northern Papua New Guinea) and Herbert (sub-equatorial northern Australia) Rivers have catchments of similar area. However, the 10yr flood exceeds the 2yr flood by only 17% in the former (equatorial) case and by about 200% in the latter (sub-equatorial) example (Yu, 1989).

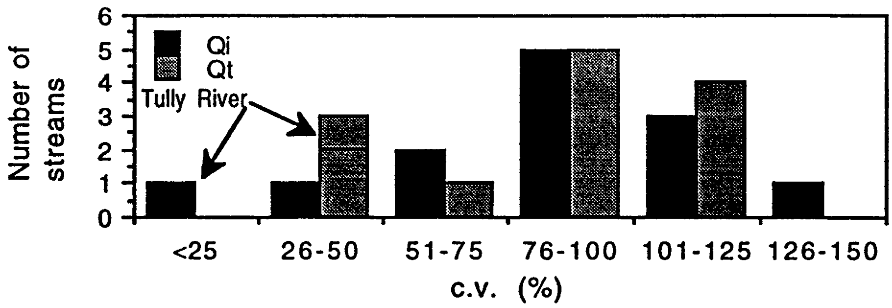


Fig. 2.1.19
Coefficient of inter-annual variation of total (Qt) and instantaneous maximum (Qi) stream flow for Queensland east coast rivers (1973-1986).

Given the highly seasonal nature of the regional rainfall, a high degree of seasonality in stream flows is expected (Fig. 2.1.20). In the Tully River, median monthly flows are greatest for the months February to April. The median monthly flow for the month of greatest runoff (April) is greater by a factor of 5.6 than that for the month of lowest flows (December). The seasonal pattern for maximum instantaneous flows differs in that very large discharges (recurrence intervals < 1:2.5 years and within 4 % of the maximum recorded) may occur in the months December to April.

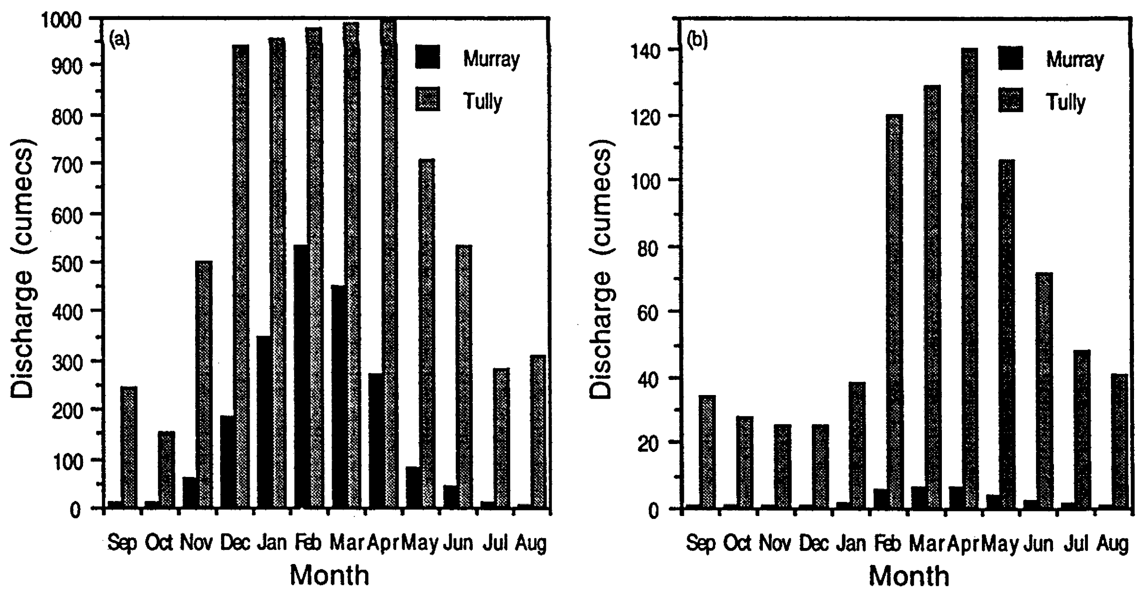


Fig. 2.1.20
Seasonal variation in instantaneous maximum (a) and median (b) stream flows in the Tully and Murray Rivers (Tully - Stn. 113006A, 12.4.1972 - 12.7.1991; Murray - Stn. 114001A, 27.5.1990 - 9.1.1991; QWRC data).

Data from Stn. 114001A on the Murray River is of very limited value in understanding the hydrology of that catchment. However, given the size, morphology, rainfall and land use patterns within the Murray catchment above Upper Murray, this catchment is likely to provide a good indication of hydrological characteristics in the major tributaries of the Tully River (ie. Davidson, Echo, Jarra and Banyan Creeks). Fig. 2.1.20 shows that seasonality of stream flow is stronger in the upper Murray than in the Tully, and that the difference between wet season and dry season flows is greater. The median stream flow for the month of greatest runoff (February) is greater by a factor of 10.2 than that for the month of lowest flows (November) compared with 5.6 in the Tully. Similarly, the maximum instantaneous discharge in February is 100 times that in August, when it is lowest. By comparison, in the Tully the difference is by a factor of only 6.6.

Flow duration curves for the Tully River at Euramo are shown in Fig. 2.1.21. The median instantaneous flow is 52 cumecs. There are marked seasonal contrasts in the flow characteristics. Low flows during the early- and mid-dry season (June, September) are greater than are low flows during the late-dry (December) and wet (March) seasons. Stream flow in June is consistently about twice that in September, throughout the range of exceedance probabilities. The flow duration curve for December roughly parallels that for March and about 98 % of the time March flows are greater by about 3 times. However, these curves converge at low frequency / high magnitude discharges.

There are two contrasts between the Tully and upper Murray (Fig. 2.1.22) flow duration curves, both of which reflect the effect of the much smaller upper Murray catchment. Firstly, flow duration curves for the upper Murray are much steeper than for the Tully, over four orders of magnitude in the former case, two orders of magnitude in the latter. Secondly, there is an upward inflection in the Murray curves at low frequency / high magnitude discharges compared with a generally downward inflection for the Tully. The contrasts between seasonal flow duration characteristics in the upper Murray catchment are similar to those observed in the Tully catchment.

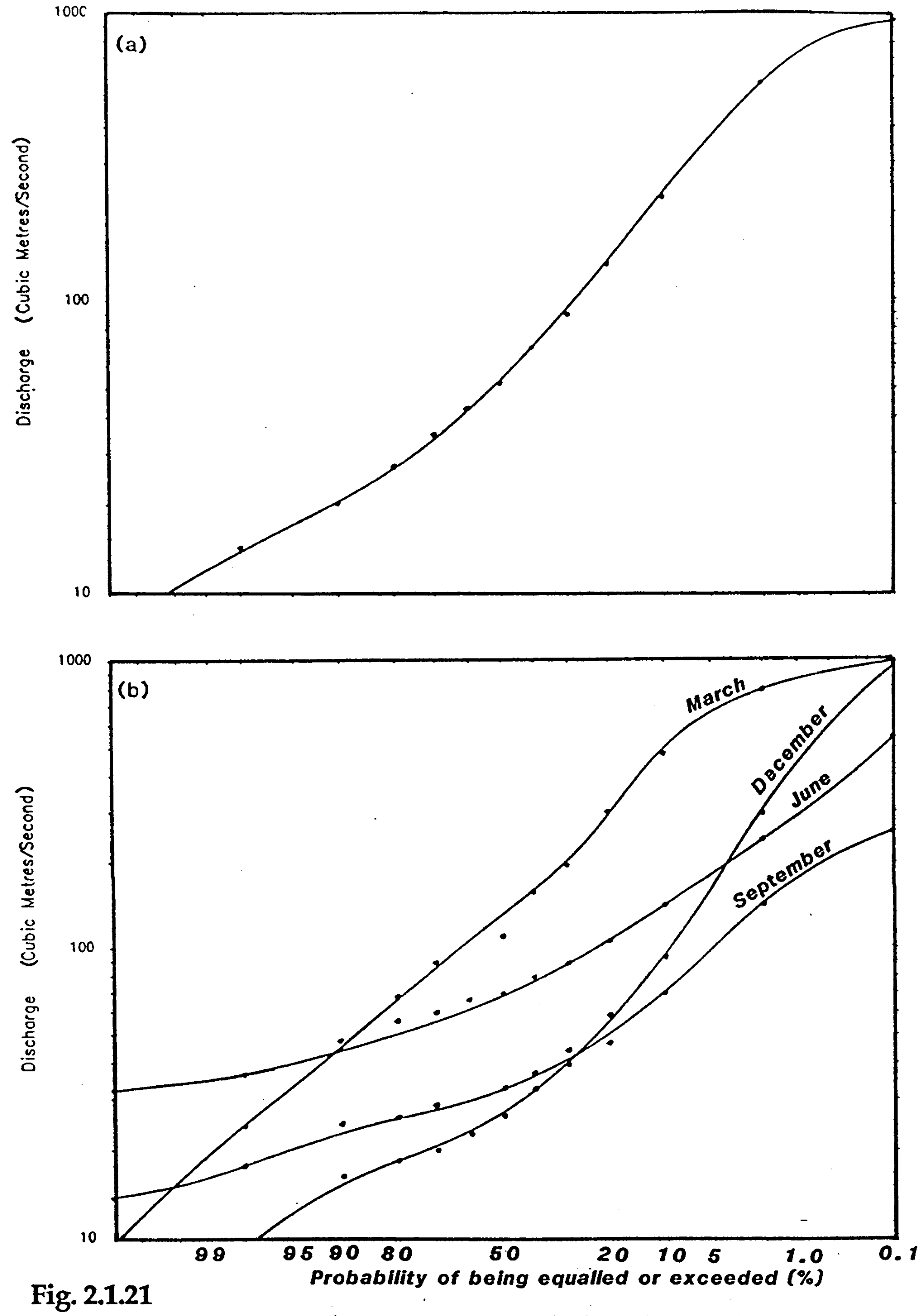


Fig. 2.1.21
Flow duration curve (Log Pearson III) for the Tully River at Euramo (Stn. 113006A) for the period 12.4.1972 to 12.7.1991; (a) - total flows, (b) - monthly flows, instantaneous flows at 4 hour intervals; QWRC data.

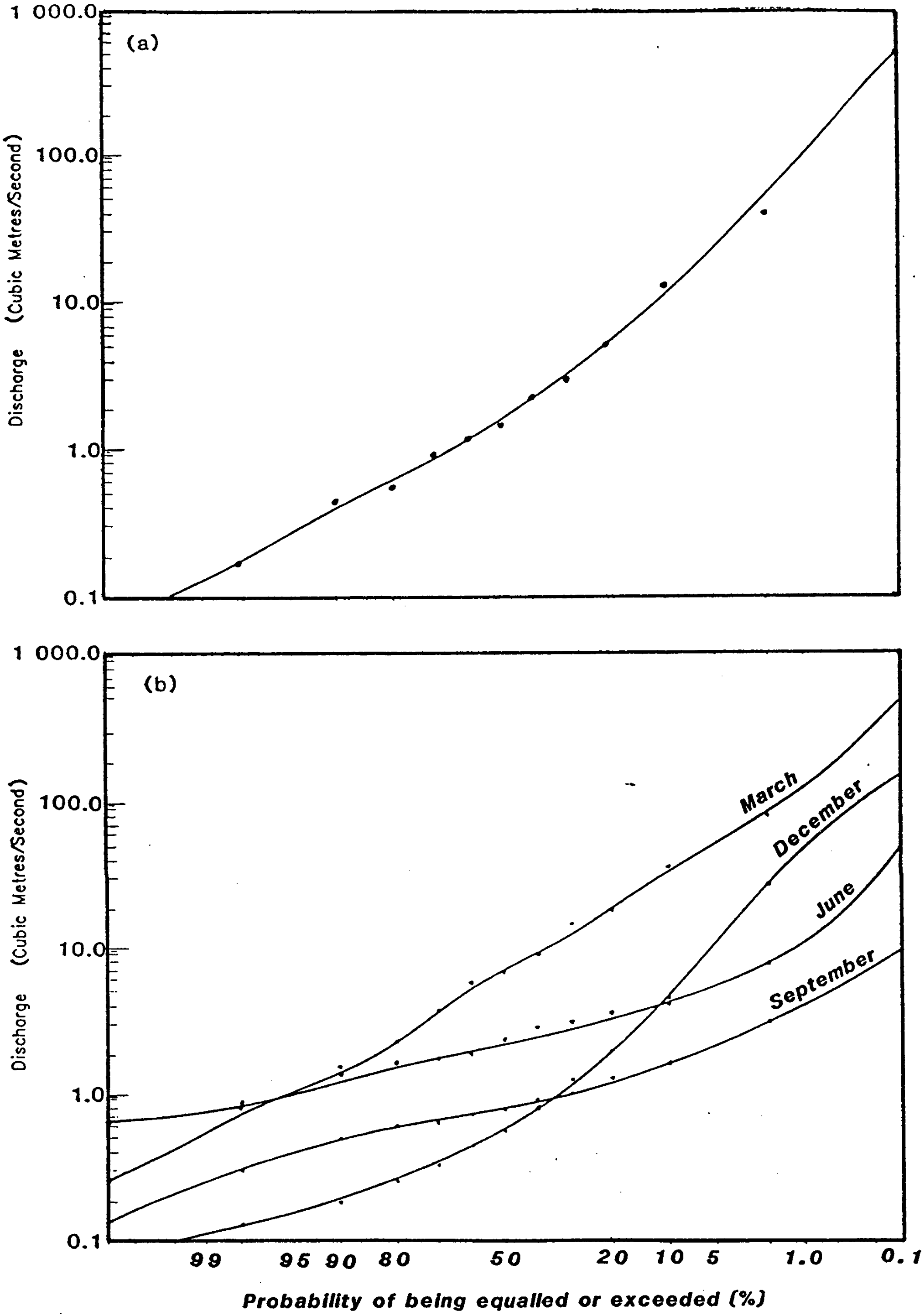
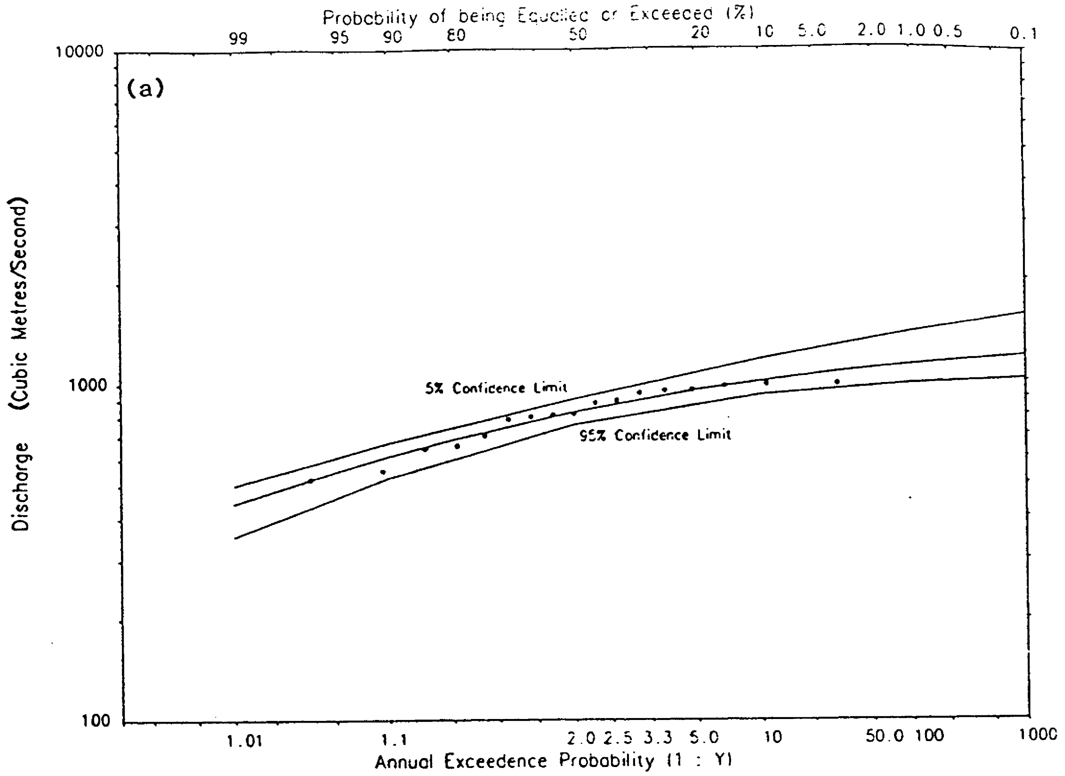


Fig. 2.1.22
Flow duration curve (Log Pearson III) for the Murray River at Upper Murray (Stn. 114001A) for the period 27.5.1970 to 9.1.1991; (a) - total flows, (b) - monthly flows, instantaneous flows at 4 hour intervals; QWRC data.

Annual and partial series flood frequency curves for the Tully (113006A) and Murray (114001A) gauging stations are given in Fig. 2.1.23 and Fig. 2.1.24, respectively. With a maximum of 20 years of record, the annual series is of limited value in this discussion given that a forty year record is probably required to estimate the mean annual flood with confidence and even longer for estimating skewness in order to fit the log Pearson III distribution (Matalas and Benson, 1968; Richards, 1982: 133).

The striking characteristic of the Tully catchment is the flatness of the curve, yielding a difference between the 2 year (924 cumecs) and 100 year (1 062 cumecs) recurrence interval discharges of only 15 %. By comparison, in the upper Murray, which is about 10 % of the area of the Tully catchment, the difference between 1:2 (303 cumecs) and 1:100 (620 cumecs) discharges is 204 %.

The foregoing summarises some significant hydrological characteristics of the Tully and upper Murray catchments, the latter probably indicative of hydrological conditions in the major tributaries of the Tully but in no way indicative of the hydrology of the lower Murray. The morphology of the lower Murray floodplain differs considerably from that of the lower Tully. In the case of the Murray, overbank flows occur very frequently (2 - 5 times.year^{-1}; Anon., 1977) and sinuosity of the channel is greater than for the Tully (1.94 v 1.60). The Murray River channel is constricted by both living vegetation and numerous logs and other debris, and there is a large volume of overbank storage in the form of numerous depressions, generally abandoned stream channels. As a result, the response of this stream to rainfall is slower than the adjacent Tully River and the recession curve is strongly protracted during drainage of the flood plain. The relationship between the Tully and Murray catchments will be further discussed in the following chapter.



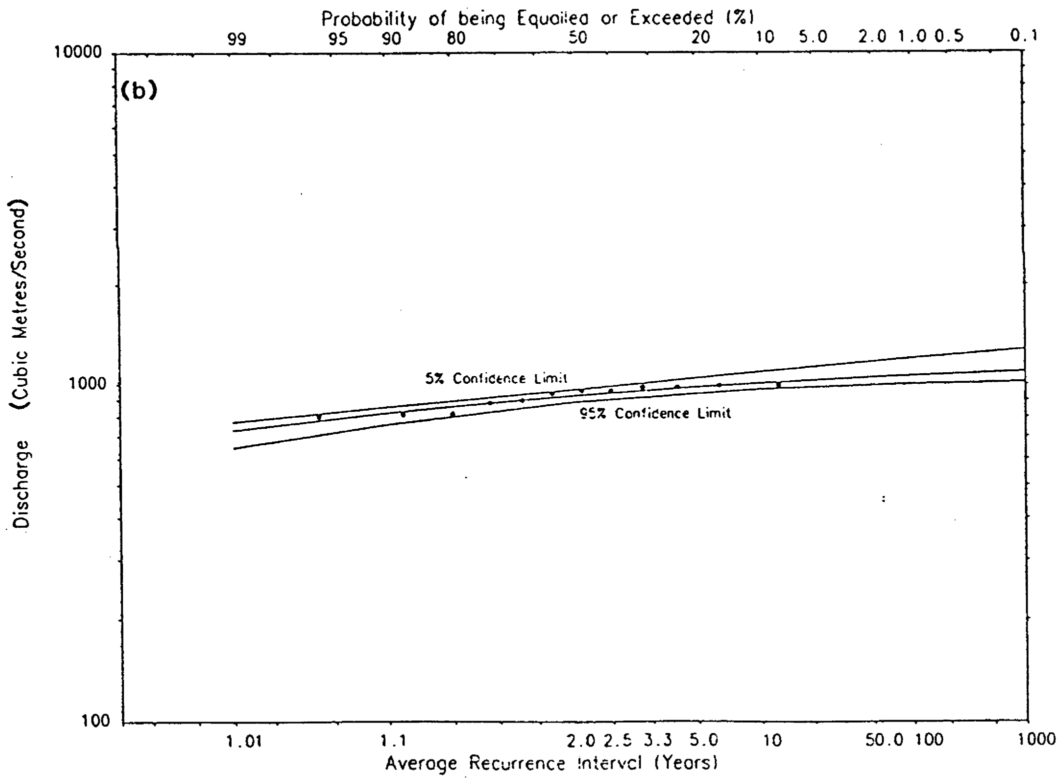


Fig. 2.1.23
Flood frequency curves (Log Pearson III) for the Tully River at Euramo (Stn. 113006A); (a) - annual series (1.1.1973 - 1.1.1990), (b) - partial series (11.4.1972 - 29.11.1990); Unpubl. QWRC plot).

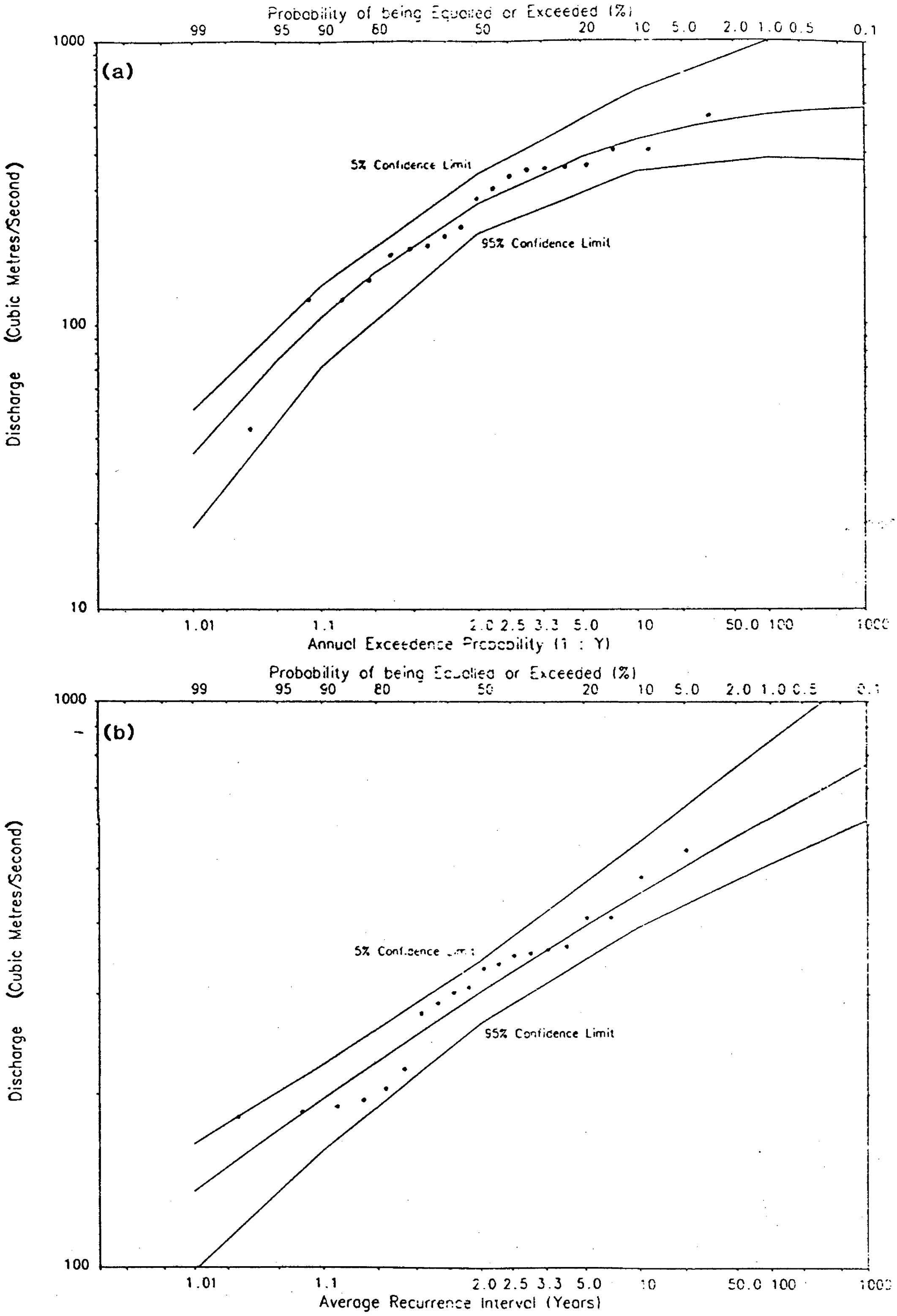


Fig. 2.1.24
Flood frequency curves (Log Pearson III) for the Murray River at Upper Murray (Stn. 114001A); (a) - annual series (1.1.1971 - 1.1.1990), (b) - partial series (26.5.1970 - 22.10.1990); Unpubl. QWRC plot).

2.1.4 Vegetation:

In the context of the present study it is important to establish the nature of the vegetation history of the catchment prior to European settlement and land use change in order to determine whether catchment conditions were "natural" or reflected a different type of anthropogenic landscape. Vegetation characteristics at the time of European settlement establish the "baseline" conditions relevant to this study and changes since that time reflect changes in land cover which largely determine the sediment yield response to land use change.

2.1.4.1 Vegetation prior to European settlement:

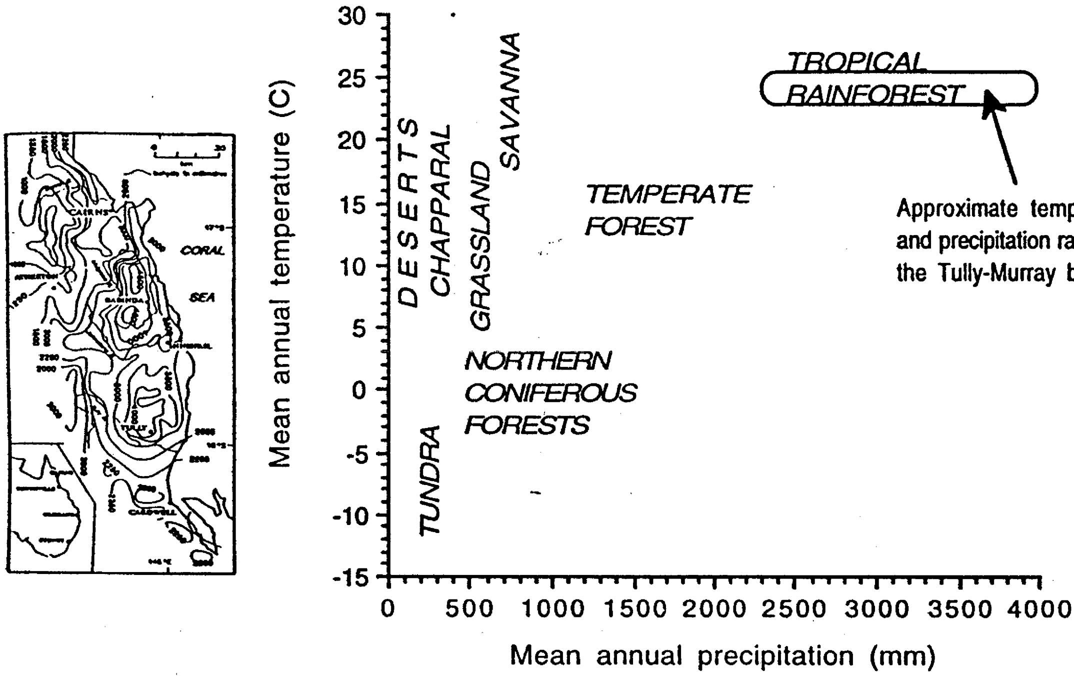
Interpretations of vegetation patterns in the Tully catchment prior to European settlement and land clearing vary, largely with respect to the characteristics of the alluvial plain. Frawley (1988) maps this area as dry sclerophyll forest with patches of open paperbark forest, and of mangroves in a wide belt paralleling the coast. Birtles (1988) maps the alluvial plain as 'swampland'.

In fact, there was a complex mosaic of vegetation. Annotations on surveyor George Phillips' "Plan of J.E. Davidson's Sugar Plantation Bellenden Plains" of August, 1870 include eight different terrain descriptions (dense scrub, dense lawyer scrub, tea tree forest, tea tree forest and devil devil country with high patches of Messmate and Lignum Vitae, dry tea tree swamp, open swampy country, open plains, and open country) in < 600 ha on the south bank of the Murray River. The lowland areas of the Banyan valley were shown as forest and "scrub" on the map by surveyor Bedford (1884), all of the valley north of Mt Mackay being so described, and the area from the Murray River south to Dallachy Creek as "open ti tree and bloodwood forest". "Scrub" is treated as synonymous with rainforest in Beale's (1970) account of Kennedy's expedition up the Tully valley. However, Birtles (1988), discussing terminology used for vegetation description in the latter part of the last century, states explicitly that "...In Australia ... the old Danish word 'scrub' applied to the vegetation of any uncleared land, 'vine scrub' was reserved for the highly complex association of lianes and herbaceous plants classified botanically as tropical rainforest...". He goes on to quote from Mulligan (1876) passages in which Mulligan is clearly using the term "scrub" to refer to tropical rainforest, not just "any uncleared land". Furthermore, Hill (1865) and Eden (1872; see quotations next paragraph) are clearly referring to complex vine forest (gallery rainforest) as "scrub" when describing the vegetation along the Tully River banks. From this it can be inferred from Bedford's map that most of the Banyan catchment was complex, lowland rainforest prior to clearing. Isolated remnants of this forest have survived (Tracey and Webb, 1975). Walsh (1959) discusses "..thick rainforest or 'scrub' as it is referred to.." in the wet tropics of northeast Queensland, showing that this usage is still current.

Interpretation of the early descriptions of the vegetation is complicated by the confusion in the literature regarding the correct names for the three major streams discharging into Rockingham Bay (Hull, Tully and Murray). It seems clear that Collinson's (1951) article, which attempts to set the record straight, is incorrect on a number of points and only serves to confuse the issue. Jones' (1961) interpretation is correct. The difference probably arises from Jones' detailed local knowledge. In the following, the current usage is placed in parentheses after the earlier or incorrect name is used. (Inconsistencies and errors in both Hill (1865) and Hill (1874) suggest that, regardless of his talents as a botanist, Walter Hill never had much idea where he actually was.)

During a botanical expedition in 1865, Walter Hill (Government botanist, Selector of Agricultural Reserves and Director of the Brisbane Botanical Gardens) climbed to an elevated position about 25 km upstream from the Macalister [Tully] mouth and observed "... extensive plains stretching towards the north, south and west, with scarcely a tree upon them, covered with luxuriant grass watered with several lagoons filled with pure water and embracing many thousands of acres of the richest agricultural land that I have seen in the Australian colonies.. beyond these plains the land is of a gently undulating character, in many places thinly timbered.." (Hill, 1865; 1231-1232). Surveyor Hull (1871a) reported on "The country between the Rivers Murray and Mackay..[Tully].., opposite the Bellenden plantation,..[which]..would make a splendid plantation, the soil being of the richest description and perfectly free from timber." and (Hull, 1871b) noted that "The country between the Rivers Murray and Mackay [Tully] is good rich soil plains, and still richer scrub lands. The plains extend for several miles, not only between the two rivers, but across the Mackay [Tully] toward the ranges to the north-west, and on both sides of the Murray.". Charles Eden, who was associated with Davidson's "Bellenden Plains" venture, described the terrain as "..unsurpassable..[with].. miles and miles of black soil plain - soil teeming with such richness - without a stick of timber, and with large lagoons scattered at intervals, besides a fine river running through its centre. Never was seen such a lovely spot to a planter's eye. No clearing, no trouble of any kind, there was the rich virgin soil only waiting for the plough.." (Eden, 1872; 289).

The extent of these grasslands is surprising given the climate of the area. The lower Tully-Murray basin lies largely within the 2 250 to 4 000 mm isohyets with a mean annual temperature of 24°C. The expected vegetation under this climatic regime would be tropical rainforest (Fig. 2.1.25) or tropical seasonal forest according to the classification of Whittaker (1975: 167), and Gentilli's (1986: 45) phytohydroxeric index also predicts rainforest.



(a) (b)

Fig. 2.1.25
(a) The 30 year mean annual isohyets for the humid tropics of northeast Queensland (from Bonell, 1988); (b) The relationship between mean annual precipitation, mean annual temperature, and the major terrestrial biomes, showing the climatic characteristics of the Tully-Murray basin (After Begon *et al.*'s (1990) modification of Whittaker, 1975).

Of course, local climate, soil and fire regimes can alter these generalisations (Begon *et al.* , 1990: 27) and possible causes of these apparently anomalous grasslands are further discussed below (Modern vegetation mapping) and in Chapter 2.3.1 (Land use and human settlement).

Hill (1865) described the banks of the lower 25 km of the Mackay [Hull] as "..extremely low, and almost uninterruptedly fringed by mangroves. The lands .. adjoining were .. lower, .. naturally swampy, and .. subject to periodical inundation with brackish water..". Hill travelled up the Macalister [Tully] by boat, noting that for the first 1.5 km the country was sandy, for the next 3 km the banks were fringed with mangroves, replaced upstream by "tropical vegetation". He also remarked on the "... peculiar density of the scrub on each bank ..[of the Tully River].., in some places..not less than a mile in breadth. In fact, I never witnessed in any of the colonies so dense or so luxuriant a growth of scrub trees and plants.." (Hill, 1865). Eden (1872; 301), described the density of the Mackay [Tully] gallery rainforest and contrasted it with the plains through which the Murray flows. On the banks of the Tully "..stood a scrub of a mile in depth that we had only penetrated by crawling along a black's track on foot..[and].. to give a just idea of the density of this tropical jungle would be beyond my power..[but]..you could not see two yards in any direction.." (Eden, 1872; 301-302).

The preceding paragraphs have described the vegetation of the study area as it was first encountered by white explorers and settlers. A significant anomaly in the distribution of the lowland vegetation has also been outlined. The vegetation of the study area has been described in a more detailed, rigorous and scientific manner over the last 30 years. The following section describes the present vegetation of the catchment, based on these modern interpretations, and pursues the question of the anomalous grasslands.

2.1.4.2 Modern vegetation mapping:

The best available mapping of the vegetation of the humid tropics region is that of Tracey and Webb (1975) with descriptions of the vegetation types that were mapped and their ecological relations in Tracey (1982). This mapping is of limited use for alluvial plain areas as it describes conditions after most of the alluvial plain was cleared.

The plateau area is generally a simple notophyll vine forest in the south, with a simple microphyll vine forest in the Cochable Creek headwaters north of the Tully River (Tracey, 1982). These forests are generally < 30m in height, have a simple structure with only two tree strata, tree ferns and palms are common, and there is a fairly dense ground layer. Epiphytes, predominantly mosses, ferns and orchids, are common. In the Koolmoon Creek area, mainly on the basaltic soils, the vegetation is predominantly a complex notophyll vine forest in which buttress roots, epiphytes and woody lianes are common. The uneven canopy ranges from 20 to 45 m in height. The drier southwest of the plateau area, in the upper Nitchiga Creek catchment on thin granitic soils, has a cover of tall, eucalyptus open forest along the rainforest fringe. The canopy is *Eucalyptus grandis, E. intermedia* and *Lophostemon conferta* at c. 25 - 45 m with a layer of vineforest species at

10 - 15m. Further down the rainfall gradient, the vegetation is low eucalyptus woodland.

The montane areas of the Tully catchment are largely Tracey's (1982) Type 2a (mesophyll vine forest) vegetation. Canopy height of this floristically variable forest is generally c. 30m, with a substorey and understorey present. In more sheltered areas with deeper, moister soils (such as drainage lines) these forests are more structurally complex and lianes and epiphytes are more common. In areas exposed to disturbance (eg. from cyclones, fire and logging) the mesophyll vine forest is often replaced by a closed forest with sclerophyll emergents and codominants. In the Mt Tyson and Mt Mackay areas and along many ridge crests in the lower Tully Gorge the emergents are generally *Acacia aulacocarpa* with an understorey of vineforest species becoming more diverse with time since disturbance.

Some well-drained lowland areas which have not been cleared (notably Kooroomool Creek and upper Jarra Creek) have a Type 1a (complex mesophyll vine forest) cover. This forest is described by Tracey (1982) as the optimum development of rainforest in Australia, occurring in humid, lowland areas where soil and climatic conditions are at their most favourable. Generally, this is on basaltic soils although in the examples given for the Tully catchment the Type 1a rainforest has developed on granitic soils.

Most areas of remnant vegetation on the alluvial plain are *Melaleuca quinquinervia* dominated forests with a canopy height of 15 m. In some areas this forest is virtually monospecific but often occurs with a dense and species rich understorey of vine forest species.

Although Tracey and Webb (1975) do not map the natural vegetation of the alluvial plain, Winter *et al.* (1987) present a map of the cleared area of the Tully catchment, communicated to them by Tracey, showing the native vegetation of the alluvial plain prior to clearing in the 1960s. Of the 429 km^2 of native vegetation mapped, 36 % was Type 1a complex mesophyll vine forest, a further 2.3 % was other types of rainforest and the remainder was predominantly coastal and floodplain complexes dominated by *Eucalyptus* and *Melaleuca* open forest and woodland. About 10 % of the area was freshwater swamp.

Much of the alluvial plain was described as grassland by the earliest observers (Hill in 1865, Hull in 1871 and Eden in 1872) who did not report the grass species present. Descriptions of the species composition of coastal grasslands elsewhere in north Queensland are available. Hill (1874) identified five species (*Anthistiria ciliata* ('Kangaroo grass' according to Hill, 1874), *Cenchus australis, Chloris divaricata, Cynodon polystochus and*

Leptaspis banksii) in coastal grasslands on Fitzroy Island, and adjacent to the Annan and Daintree Rivers.

Walsh (1959) lists kangaroo grass (*Themeda australis*), black spear (*Heteropogon contortus*), giant spear, *Aristida* and wire grass spp., and *Brachiaria* spp. in wetter areas, in the open country of the lowland wet tropics and Sweeney (1961) refers to "blady grass plains" on the Tully River alluvial plain. The composition of grasslands on the Herbert River floodplain is discussed by Tracey (1968). At the wet/dry margins *Imperata cylindrica* (Blady grass) and *Mimosa pudica* dominate, and with decreasing moisture/increasing elevation communities including *Themeda, Heteropogon, Ischaemum and Sorghum spp.* occur. The presence of *I. cylindrica* and *M. pudica*, to the exclusion of other species, in some areas is attributed to frequent burning. Tracey (1968) describes the Herbert River grasslands as resembling those of the Sub-Coastal Plainland System (Christian and Stewart, 1953) of Arnhem Land, in which region floodplains are burnt thoroughly throughout the dry season on an annual basis under Aboriginal land management regimes (Jones, 1980; Haynes, 1985). Teitzel and Bruce (1971) stated that the common grasses in the treeless plain areas of the northeast Queensland wet tropics region were *Imperata, Heteropogon, Themeda, Aristida, Eragrostis, Ischaemum,* and *Panicum* spp.. Of these species*Imperata cylindrica, Heteropogon contortus* and *Themeda australis* are widely recognised as being tolerant of, adapted to and competitively advantaged by fire (Walsh, 1954; Webb, 1977; Leigh and Noble, 1981; Johnson and Purdie, 1981; Mott and Andrew, 1985) and blady grass plains are typical fire seres adjacent to rainforest in other tropical countries (Webb, 1977). Webb (1977) regards the blady grass plains of the Lockhart River floodplain (rainfall only 65 % of that for the Tully/Murray floodplain) as anomalous in an area in which there is no apparent reason that vineforest could not establish.

The grasslands of the Tully/Murray alluvial plain may have been created and /or maintained by aboriginal burning and the vegetation types evident on the 1961 air photos prior to clearing in the 1960s and 1970s may be, at least in part, regrowth subsequent to cessation of aboriginal land management practices (see Ch. 2.3 below). However, although the classification of Tracey and Webb (1975) and Tracey (1982) includes a "Fire degraded grassland with woody regrowth" class, Tracey maps no such class for the Tully alluvial plain (Winter *et al.*, 1987).

In the coastal beach ridge and swale terrain the Melaleuca forest often overlaps with the *E. pellita* and *E. tessellaris* dominated coastal woodlands (Tracey, 1982). Along foredunes *Casuarina equisetifolia* var. *incana, Acacia* *crassicarpa, Scaevola frutescens* and *Eugenia banksii* are common. Like the Melaleuca forests of the alluvial plain, these areas will often occur as complexes with mosaics including various rainforest and eucalypt forest types.

In the immediate vicinity of the Hull, Tully and Murray River mouths, *Rhizophora*-dominated mangrove communities occur.

In summary, most montane and plateau areas have a vegetative cover of rainforest of varying floristics and structural complexity. Exceptions are in the southwest of the plateau area (drier, with Eucalypt woodland) and areas of disturbance (eg. Mt Tyson and Mt Mackay). The alluvial plain was, before clearing, a complex mosaic of grasslands, Melaleuca forests and woodlands, with extensive rainforest patches, particularly riparian rainforest. The valley floors of the major tributary streams (eg. Banyan, Jarra, Kooroomool, Echo and Davidson Creeks) were largely Type 1a complex mesophyll vine forest. The complex coastal vegetation mosaic includes many of the communities found elsewhere in the catchment, as well as distinctly coastal foredune and mangrove communities.

2.1.4.3 Island vegetation:

Descriptions of the vegetation on the islands of Rockingham Bay from the time of European arrival include:-

June, 1815 - "lofty wooded island" (Cunningham in Lee, 1925;428: Goold Island)

June, 1819 - "..so thickly covered with undergrowth and climbing plants as to render it perfectly inaccessible." (King, 1827; 204: Smith Is. (Banfield (1908; 25-26) and subsequently Jones (1961; 9) state that this was Timana Island. However, careful reading of King's journal, consideration of Cook's journal and the reference King makes to it, and of the latitude given (determined on shore, not from the deck of the *Mermaid*) lead to the clear conclusion that Smith is the island on which King landed.); "..wooded hills..separated from each other by deep valleys.." (King, 1827; 204: Dunk Is.)

c. 1870 - "..covered with dense vegetation" (Eden, 1872; 293: Family Group Islands)

1873 - "..steep, and covered with thick woods.." (Dalrymple, 1874; 619: Family Group Islands); "..well studded with trees and shrubs.." (Hill, 1874; 666: Brook Islands)

1896 - 1908 - "..the range is heavily draped with jungle .. on the western aspect. .. on the weather or eastern side, low-growing scrub and restricted areas of forest, with expansive patches of jungle, plentifully intermixed with palms and bananas..[On].. the plateau.. grows the best of the bloodwoods

(*Eucalyptus corymbosa*), the red stringybark (*E. robusta*), Moreton Bay ash (*E. tessalaris*), various wattles, and the gin-gee tree of the blacks (*Diplanthera tetraphylla*). *Pandanus aquaticus* marks the courses and curves of some of the gullies. On the flat, the plateau and the hillside the forest consists of similar trees .. the one that does not leave the flat being the tea-tree or melaleuca. In some places the jungle comes down to the waters edge.." (Banfield, 1908; 15-16: Dunk Is.)

Most of Dunk Island has a vegetative cover similar to the "disturbance forest" common on Mt Mackay and Mt Tyson. On Dunk Island the *Acacia mangium* and *A. aulacocarpa* canopy reaches 20-30 m with a 10-20 m vine forest understorey. In some areas *Eucalyptus* spp. are co-dominants. In the less exposed areas, a structurally complex mesophyll vine forest vegetation with lianes and epiphytes occurs (Tracey and Webb, 1975). This pattern of vegetation is similar to that occurring on the smaller islands of the Family Group, although in these cases the forests tend to be drier and less complex.

Most of the area of Quaternary sediment accretion on the southwest of Dunk Island has been cleared for an airstrip and tourist resort development. However, along the coastal margin of this area is a remnant strip of the beach ridge and swale complex, similar to that previously described for mainland sites.

2.2 MARINE PHYSIOGRAPHY:

> *"Brammo Bay has its garden of coral - a border of pretty, quaint and varied growth springing up along the verge of deep water. It is not as it used to be..."*
>
> E.J. Banfield, "Confessions of a Beachcomber", Dunk Island, 1908.

Rockingham Bay extends from 17°55'S to 18°15'S and from 146°E to 146°17'E. It is roughly triangular in shape, the base of the triangle being the north coast of Hinchinbrook Island. In the context of the present study, Rockingham Bay is taken to extend from the northern coast of Hinchinbrook Island in the south to the northern tip of Dunk Island in the north. Its eastern boundary (approximately the 15 m isobath) stretches from Cape Sandwich in the south, includes the Brook Islands and the east coast of Dunk Island. The western boundary is the mainland coast from Cardwell to Tam O'Shanter Point. The area within these boundaries is approximately 700 km^2 (Fig. 2.2.1).

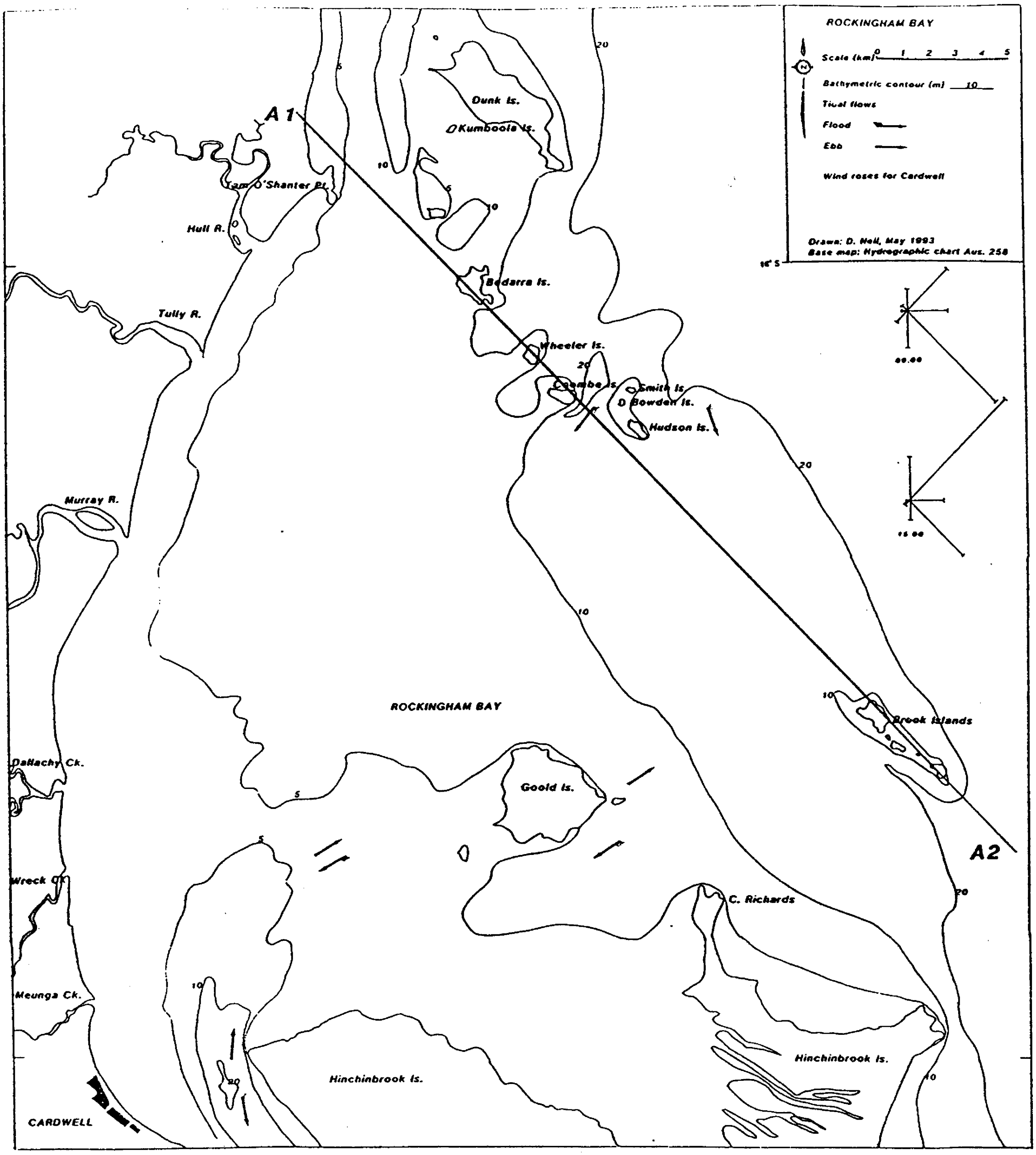


Fig. 2.2.1
Bathymetry of Rockingham Bay, also showing tidal currents and wind roses for Cardwell.

The total catchment area of Rockingham Bay is 3 110 km^2 of which the Tully River catchment contributes 51 %, the Murray River (16.5 %), the Hull River (3.5 %), streams draining directly to the Bay from south of the Murray catchment (11.5 %) and those draining to Rockingham Bay in the Missionary Bay area of Hinchinbrook Island contribute 4 %. Streams draining to Hinchinbrook Channel from both the mainland and Hinchinbrook Island comprise 13.5 % of the total catchment.

Strong tidal flows (c. 1.5 $m.s^{-1}$) occur between Hinchinbrook Channel and southern Rockingham Bay. The northern boundary is a narrow (4.1 km wide) channel between Dunk Island and Mission Beach. Along the seaward boundary some protection is afforded by the continental islands of the Family and Brook Groups. From the northeast these islands present a barrier of about 55 % permeability, but from the southeast the permeability is about 75 %.

2.2.1 Bathymetry and physical oceanography:

Bathymetry in eastern Rockingham Bay is aligned with the structural trend and, along the mainland coast, with the beach alignment. Most of Rockingham Bay, west of Coomb and Goold Islands, is < 10 m in depth. The Bay is very shallow in the south (< 6 m) but deepens further south into the Hinchinbrook Channel. All of the islands of the Family Group (except Smith, Bowden and Hudson), Brook Islands and Goold Island lie within the 10 m isobath. There are relatively deep channels between the Family Group Islands (Fig. 2.2.2), in some cases holes rather than channels, the deepest of which is immediately east of Coomb Island and c. 30 m deep.

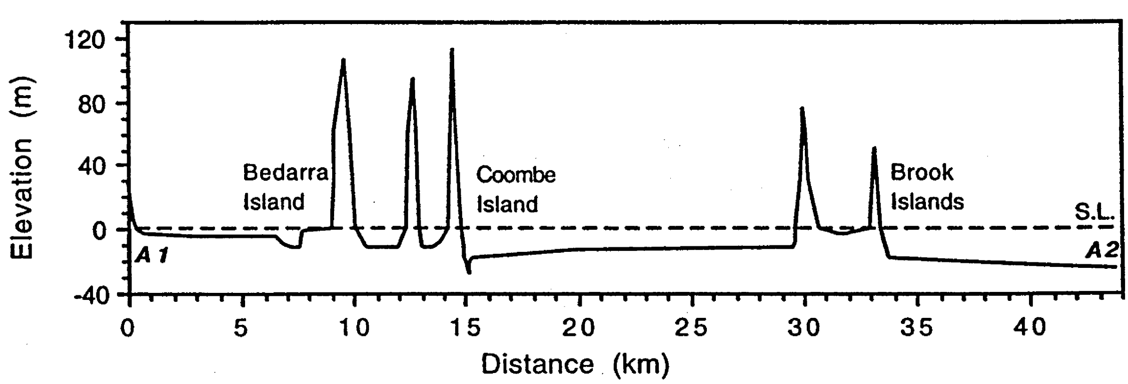


Fig. 2.2.2
Topographic and bathymetric profile of Rockingham Bay, and Family and Brook Islands (Transect location denoted A1 - A2 on Fig. 2.2.1).

Tidal ranges increase northward along the Queensland coast to a maximum in Broad Sound, north of which they decline, increasing again north of Princess Charlotte Bay toward Torres Strait. Tides at Rockingham Bay are controlled by an amphidromic system in the northern Coral Sea with a range of 2.0 m and 1.9 m at springs for Dunk and Goold Islands, respectively. Church *et al.* (1985), concluded that tides in the Palm Passage area flooded onshore and Kelly and Andrews (1985) found that this offshore-onshore flow during the ebb-flood cycle also occurred within Bowling Green Bay (19.3^{o}S). In Rockingham Bay, this pattern is strongly modified by the influence of the Hinchinbrook Channel such that the ebb-flood cycle occurs as a northeast-southwest flow. As a result, tidal currents are roughly mainland shore parallel within the Bay, and normal to the structural alignment of the offshore islands. This pattern is consistent with the findings of Andrews and Bode (1989) who showed that, although the offshore-onshore flow during the ebb-flood cycle is widespread in the GBR lagoon, in nearshore areas the pattern becomes obscure.

Flushing times (or residence times) at a shelf-wide scale are controlled by drift currents, weather-band currents and tidal currents and in the central GBR lagoon the shortest exchange time is that induced by the equatorward, longshore drift component (Andrews and Pickard, 1990). Tidal current induced exchange is of relatively minor importance, and the predominantly shore parallel oscillation is likely to further reduce its effect in Rockingham Bay.

Fluctuations in water level associated with tropical cyclones occur in the form of storm surges, as increased water level on the southern side and decreased water level on the northern side of the approaching cyclone. Surge height is influenced by meteorological factors, coastal elevation and offshore morphology (Hopley, 1982) and the impact is modified by the tide height at the time of the surge. Storm surge predictions for Cairns (16^{o}55'S), which has a similar depth correction factor (Hopley and Harvey, 1979) and tidal range to Rockingham Bay, are shown in Fig. 2.2.3. A storm surge of 3.1 m was reported for Innisfail (16^{o}55'S) during a 946 mb central pressure cyclone in 1918 (Hopley and Harvey, 1979). Storm surges are unlikely to have any direct impact on the fringing reefs of Rockingham Bay, but may have an indirect effect by contributing to the alteration of the morphology of leeward sandspits on offshore islands. Terrestrial storm surge effects include coastal flooding and increased magnitude and duration of riverine flooding.

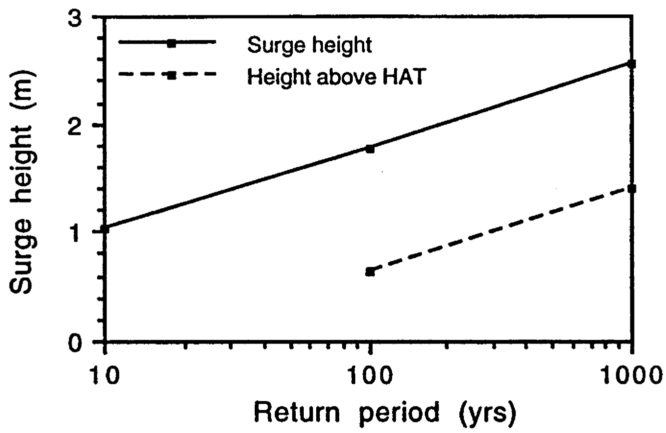


Fig. 2.2.3
Storm surge predictions for 100 km of coastline centred on Cairns (data from Hopley and Harvey, 1979).

2.2.2 *Wind and wave climate:*

In the context of the present study, the aspects of the wind climate most relevant to the physical oceanography of Rockingham Bay are twofold. Firstly, the onshore wind energy and its role in wave generated bottom sediment resuspension and, secondly, the relative importance of northerly and southerly winds and their role in windforced surface current generation which can influence the direction of propagation of buoyant river plumes.

The first of these considerations is addressed in Fig. 2.2.4. Onshore wind energy is calculated as a cubic function of the velocity of winds (09.00 and 15.00 hrs) from the northeast, east and southeast for the period of record (Cardwell data). Percentages given are of the winds from these directions only. Cardwell's position in the lee of Hinchinbrook Island renders it less than ideal for accurate determination of the wind climate of the study area. However, this is balanced by the relatively long period of record.

Onshore wind energies are clearly greatest during the late dry period (September - November), prior to the onset of the wet season. They are at their lowest during the wet season months of February, March and April and in May. Although the pattern is strongly seasonal, there is only a twofold difference between the onshore wind energies in the high energy and low energy months. One implication of this pattern is that there is likely to be some separation in time of suspended sediment in Rockingham Bay waters due to bottom sediment resuspension and sediment plume propagation. However, this separation is limited by the relatively low seasonal energy contrasts and by the possibility of high wind energy occurring at the same time as early wet season runoff events (December and

January). This time-averaged analysis has its limitations and, ultimately, these relationships must be considered on an event basis.

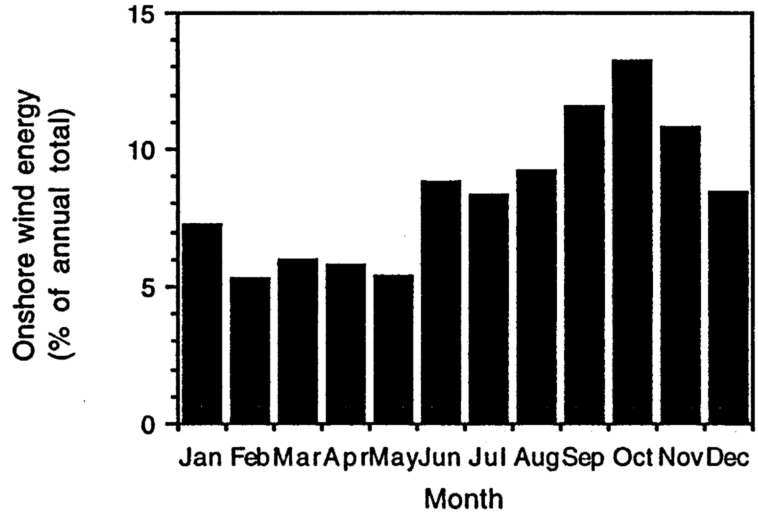


Fig. 2.2.4
Monthly variation in onshore wind energy at Cardwell (calculated as velocity^3 of winds from NE, E and SE).

There is a marked seasonal contrast in the relative importance of northerly and southerly winds at Cardwell (Fig. 2.2.5). Winds likely to induce northward plume movement are taken to be from the SE, S and SW. Those inducing southward plume movement are from the NW, N and NE. Winds from the east and west are regarded as neutral and not included in the analysis, which also ignores the subtleties of wind effects on surface water circulation in Rockingham Bay.

The seasonal contrast is very strong, although the greatest contrasts are in the pre- and post-wet season periods and therefore not as relevant to the question of plume movement. The results suggest that river plumes from early-wet season floods are most likely to propagate southward, those from late-wet season floods are more likely to be wind-forced northward and those in February could go either way. The relatively low magnitude floods which occur in May, June and July are likely to be strongly advected northward. Floods during September, October and November when the probability of southward advection is greatest are insignificant in magnitude. The role of wind-forcing in river plume dynamics must be seen as a modifying influence on the northward geostrophic longshore current, which is discussed in Ch. 5. Ultimately, these relationships must also be considered on an event basis.

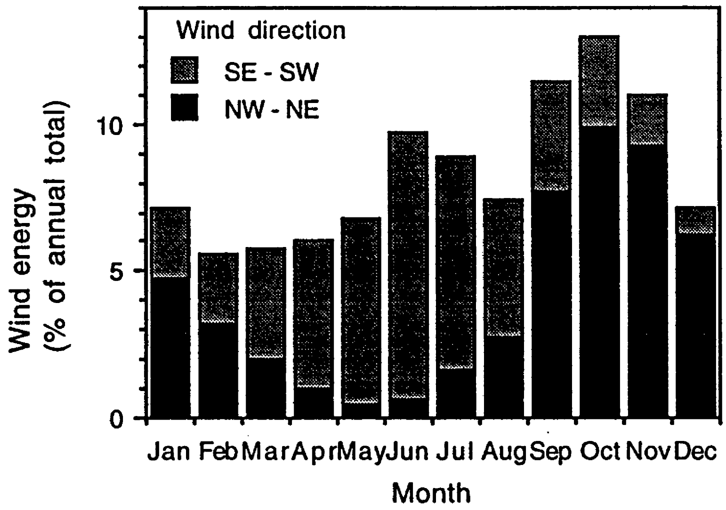


Fig. 2.2.5
Monthly variation in the relative frequency of northerly and southerly wind energy at Cardwell (calculated as wind velocity^3).

In addition to seasonal variation in wind energy and direction, significant temporal variations in the frequency of strong winds (22 - 33 knots; those capable of resuspending bottom sediments in shallow coastal waters) occurs along the north Queensland coastline (Fig. 2.2.6). The time series shows that there is considerable variation between sites (attributed to differing aspect, elevation and exposure) and that the wind histories for the three sites are not consistent.

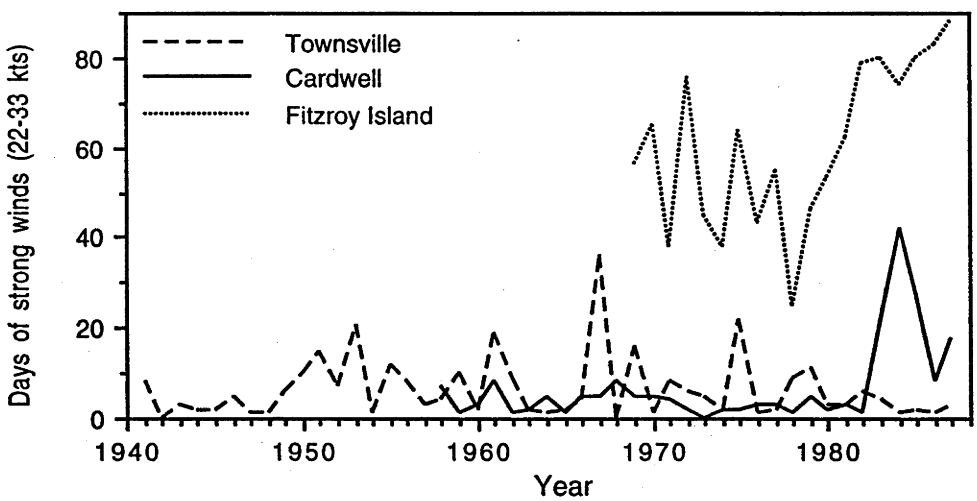


Fig. 2.2.6
Time series of strong wind occurrence on the north Queensland coast (Aust. Bur. Met. data).

The wave climate of Rockingham Bay is dominated by the wind climate modified by the filtering effect of the offshore reefs. Wave heights generally decline northwards along the Queensland coast due to the presence, and decreasing distance offshore, of the GBR. For example, Hopley (1982) showed that a significant wave height (H_{sig}; defined as the mean of the highest 1/3 of the waves recorded) of 1.15 m may be exceeded 50 % of the time at the Gold Coast (29°S), whereas at Yeppoon (23°S) H_{sig} 50 % was 0.8 m and at Cairns (17°S) was only 0.5 m. Fig. 2.2.7 shows the exceedance probabilities for summer and winter significant wave heights at Cairns. These data were acquired, using a "Waverider" buoy-mounted accelerometer, for the period May, 1975 to December, 1981. During this period, ten cyclones with central pressures ranging from 988 - 998 mb passed within an area 400 km north and 50 km east of the buoy. For wave heights of < 1.0 m, waves of a given height occur more frequently in winter than in summer. Wave heights > 1.4 m are generally associated with cyclones and consequently occur almost exclusively in summer (BPA, 1984).

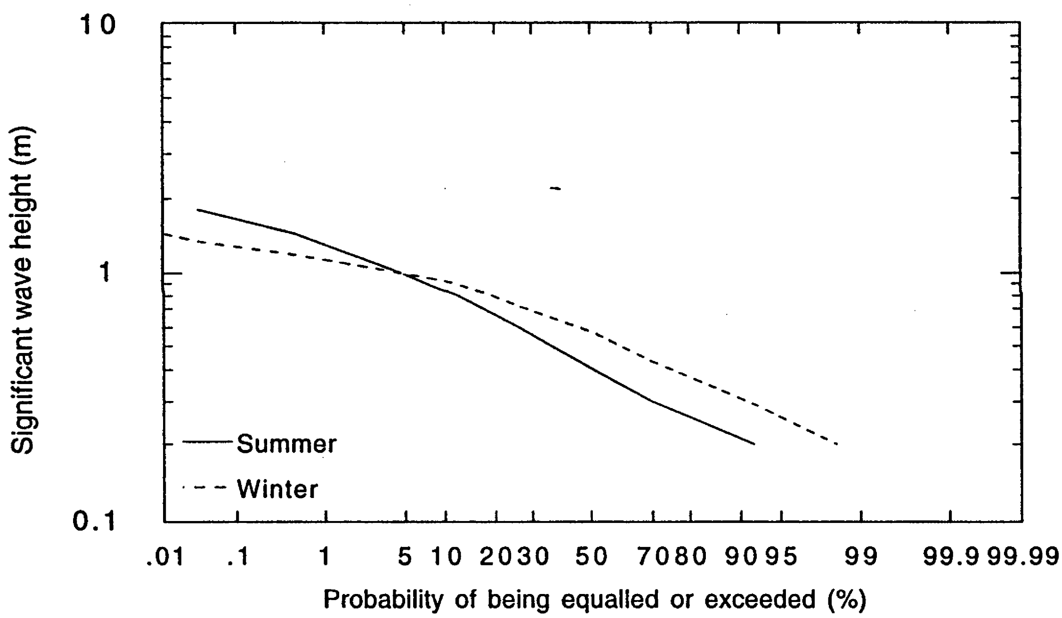


Fig. 2.2.7
Probability of exceedance times for significant wave heights (H_{sig}) at Cairns (May, 1975 - December, 1981; data from BPA, 1984).

A time series of mean wave height, derived from COPE (Coastal Observation Program (Engineering); Beach Protection Authority, Queensland) data (Robinson and Jones, 1977), at Hull Heads for the period 1980 to 1989 is given in Fig. 2.2.8. It is clear that there is considerable inter-annual variability. For example, the mean wave height in 1986 is < 60% of that for 1985. Bimodality occurs in some years, with peaks occurring in the late-wet season months and again in the late-dry period, although the exact timing of these peaks is quite variable. In some years the wet season mode is highest, and in others the mode occurring in the late dry is highest. As many as four distinct monthly peaks in wave energy may occur in a single year. These results are in contrast to the seasonal wind pattern at Cardwell (Fig. 2.2.4) which contains little to suggest the occurrence of high waves in the late-wet season. The seasonal wave pattern suggests that wave resuspension of bottom sediments could occur at any time of the year, and is as likely to occur in the wet season as the dry season.

It is clear from Figs. 2.2.4, 2.2.7 and 2.2.8 that low frequency, high energy cyclone conditions are responsible for the highest wave energies occurring in the wet season, but these events are extremes in a period of otherwise relatively low wave energy. Because the maximum rate of sediment resuspension is associated with the extreme wave conditions (cyclones) and the maximum stream sediment concentrations are associated with extreme rainfall and streamflow conditions (cyclones), sediments derived from both sources will often be in suspension in Rockingham Bay waters concurrently.

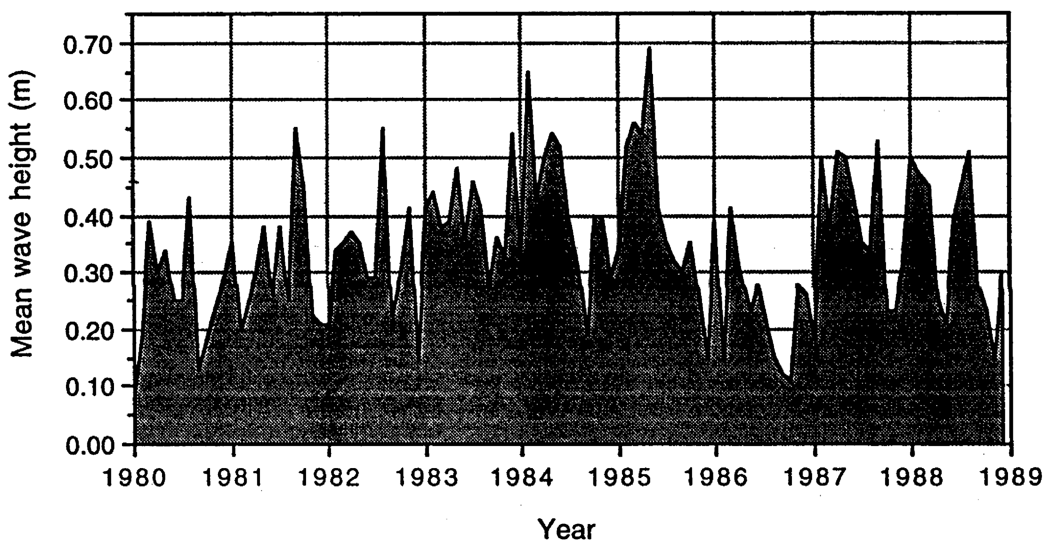


Fig. 2.2.8
Variation in mean wave height (monthly means) at Hull Heads for the period 1980-1988 (data from BPA, 1989).

The relative proportion of northward and southward littoral current directions also varies on an inter-annual as well as seasonal basis (Fig. 2.2.9). During the years 1980, 1987 and 1988, for example, littoral currents were predominantly northward and in 1982, 1983, 1984 and 1985 southward currents prevailed. A strong seasonal pattern is evident, with northward littoral currents much more common in the first half of a given year than in the last half. The seasonal patterns of littoral current direction are generally consistent with the interpretation of the wind climate illustrated in Fig. 2.2.5.

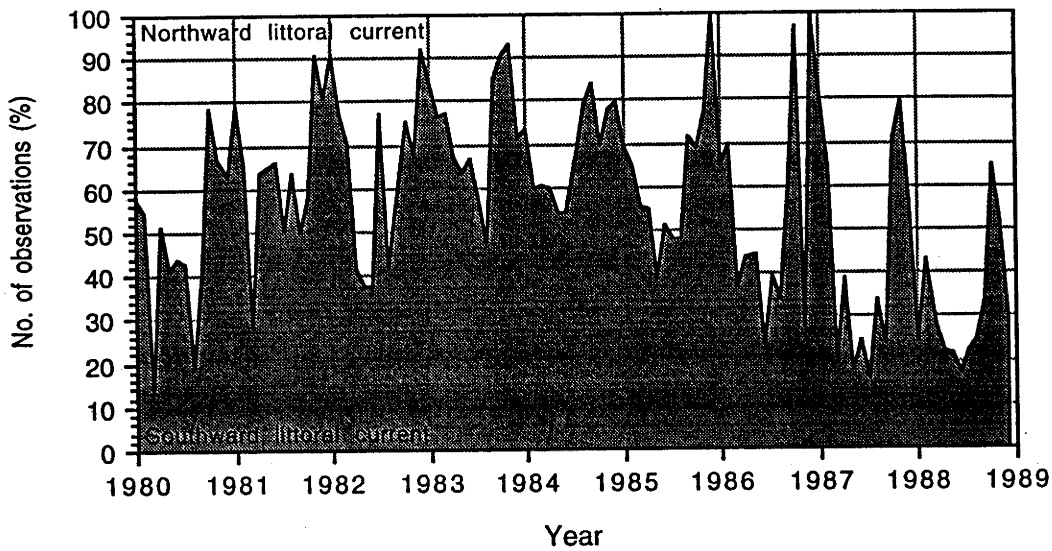


Fig. 2.2.9
Variation in littoral current direction at Hull Heads for the period 1980-1988 (observations when no current was observed were excluded; data from BPA, 1989).

Surface water temperatures in the inner GBR lagoon (at 16 - 17^{o}S) follow a seasonal cycle with an amplitude of 6 - 7^{o}C (Fig. 2.2.10). The seasonal pattern is similar to that of air temperatures (Ch. 2.1.2), with the warmest waters in January and the coldest in July. Salinity variations are largely controlled by fluvial inputs and direct rainfall, with some evaporative concentration occurring in the early summer, prior to the onset of the wet season (Fig. 2.2.10). Although seasonal temperature variations are likely to be generally consistent between years, the temporal pattern of salinity variation is controlled by the time of onset, intensity and duration of the wet season.

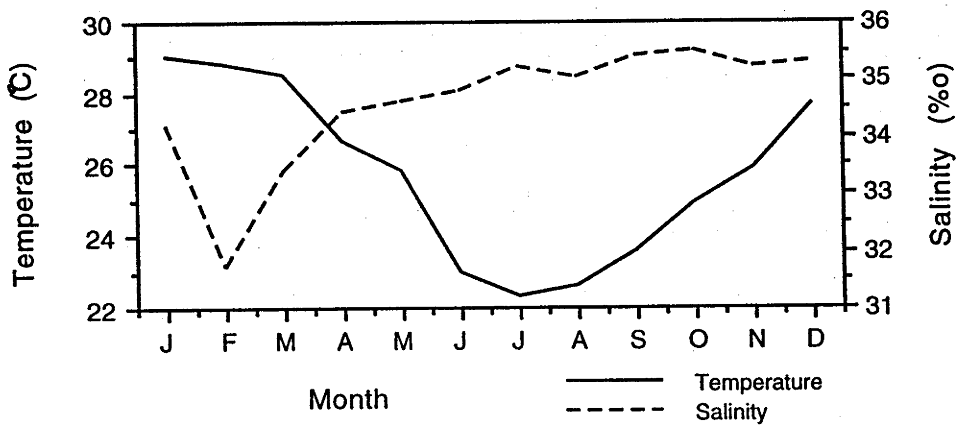


Fig. 2.2.10
Seasonal temperature and salinity profiles for the inner GBR lagoon, at 16 - 17^{o}S. (data from Pickard, 1977; Hopley, 1982).

2.2.4 *Islands and reefs:*

The characteristics of the subtidal zone adjacent to the Family Group islands differ between the northeast and southwest aspects. The southeast and northeast quadrants are subjected to greater wind and wave energies, have steep slopes with little coral growth and the seabed cover is largely granite boulders (often 3 - 4 m diameter) with a dense cover of macroalgae. The high algal cover observed is consistent with the results of Littler *et al.* (1991) for high, granitic islands in the Seychelles Archipelago. The relatively sheltered southwest and northwest quadrants have gentler slopes with a higher proportion of the seabed having a calcareous sand cover and some coral growth. Coral growth is largely massive colonies of *Porites* spp., this genus generally having a relatively low tolerance of high wave energies (Rosen, 1975; Geister, 1977; Done, 1983), but a tolerance of high rates of sedimentation (Hubbard and Pocock, 1972). The distribution of coral growth on these island fringing reefs appears to be limited by the restricted availability of a suitable substrate and by water turbidity. Corals are largely confined to shallow waters (c. 2 - 3 m deep at LWS) as a consequence of these two factors, and many massive colonies are at or very close to the tidally controlled limit of upward growth.

Although fringing reefs of the Family Group are dominated by massive corals at the present time, in the past luxuriant growth of branching corals occurred on the north coast of Dunk Island. Their susceptibility to damage by wave action and suspended sediment resuspension is indicated by the following passage from Banfield (1908:129):

> *"A storm in March, 1903, which did scarcely any damage to vegetation ashore, destroyed most of the fantastic forms which made the coral garden enchanting. In its commotion, too, the sea lost its purity. The sediment and ooze of decades were churned up, and, as the agitation ceased, were precipitated - a brown, furry, slimy mud, all over the garden - smothering the industrious polyps to which all its prettiness was due."*

Hopley (1971), citing Hedley (1925) and Rainford (1924-26), states that ".. the death of the coral..[on the island fringing reefs].. is in part the result of fresh-water flushes resulting from cyclonic rainfall on the mainland". During January, 1918 two severe cyclones struck the Queensland coast, the first at Babinda and the second at Mackay. Although Banfield describes the destructive effects of the Babinda cyclone on the vegetation of Dunk Island, he makes no mention of effects on its fringing reefs. Rainford (1924-26) reports that during the 1918 Mackay cyclone, rainfall at Bowen was 660 mm in five days coincident with a period of low night tides. Extensive destruction of fringing reefs in Edgecumbe Bay (Stone and Middle Islands) and the Whitsunday Group resulted. Terrestrial runoff was also the reason for coral death on fringing reefs of the Keppell Group during the 1991 Fitzroy River floods (van Woesik, 1991).

Apart from these small fringing reefs on the islands, there are no other reefs or reefal shoals in Rockingham Bay, the nearest being Kennedy Shoal, about 42 km offshore, and small fringing reefs northward along the mainland coast.

2.3 LAND USE AND HUMAN SETTLEMENT.

2.3.1 Land use change:

2.3.1.1 Pre-European land use:

Prior to European settlement, the Rockingham Bay area was occupied by four Aboriginal tribal groups (Tindale, 1974), part of a group of twelve pygmoid tribes occupying the northeast rainforests, and argued by Tindale and Birdsell (1941) to be racially distinct. Harris (1978), using data published by Parry-Okeden (1897), estimated population densities of lowland tribes at 1:3.3 km^2 and of upland tribes at 1:10.5 km^2. Assuming that populations prior to the impact of European settlement were about 2.5 times as great as the 1897 estimates (Harris, 1978) pre-contact population densities of 1:1.3 km^2 (lowland tribes) and of 1:4 km^2 (upland tribes) were likely.

Relatively little is known of their impact on the regional environment, although Harris (1978) provides a discussion of resource use (predominantly vegetable foods) and of the seasonal cycles of resource availability and hunting mobility. Kershaw (1986) has suggested that changes in the composition of fossil pollen in sediment cores from the Atherton Tableland and associated increases in the charcoal content of those sediments could be a consequence of the arrival of aboriginal people in the area and application of their land management practices, notably the use of fire. This practice was widespread in Australia (Jones, 1969) and has been inferred from palynological (Singh and Geissler, 1985) and historical (Nicholson, 1981) evidence in other locations as well as being a continuing aboriginal land management practice, particularly in northern Australia (Haynes, 1985). In the absence of local sedimentological or palynological evidence, landscape descriptions from the earliest explorers are the best data source from which inferences of aboriginal land management practices can be drawn.

The first description of the Rockingham Bay area comes from the "Endeavour" voyage of James Cook, who sailed between the Smith, Bowden and Hudson group and the inner Family Islands on June 8th, 1770. He saw "...on one of the nearest Islands a number of the natives collicted together who ... were quite naked and of a very dark Colour with short hair". No description of the terrain is given by Cook (Beaglehole, 1968). Banks noted that the mainland "..lookd rather less barren than usual.." (Beaglehole, 1962;76), but makes no further comment on the terrain.

Cook noted smoke ("... some very large smooks"...), attributed to the presence of aboriginals, north of Cape Upstart, "... smooks in several places ..." at the southern end of Cleveland Bay and several "... very large smooks upon the main..." adjacent to the Palm Group. Cook makes no mention of fires in the Rockingham Bay area, but notes what were apparently campfires along the mainland shore south of the Franklands (Beaglehole, 1968; 388-342). On June 8, 1770, Banks observed that "..by the number of fires..[the mainland Rockingham Bay area]..seemd to be better peopled..[than areas further south]" (Beaglehole, 1962;76). On June 21, 1819, King (1827; 204) noted that "..the smoke of their [aboriginals] fires, as usual, lined the coast..". Cunningham (in Lee, 1925; 428-429), also travelling in June (of 1815), made no mention of fires in his journal.

Jukes (1847), who was in Rockingham Bay from 19.5 to 1.6.1843, observed that "...the natives of Rockingham Bay were very numerous", also noted their presence on the islands (Goold Island in this case) and described their canoes. Five years later, from 23.5 to 8.7.1848, Edmund Kennedy travelled south along the Rockingham Bay coastline from Kennedy Bay to Meunga Creek, and then northwest up the Tully valley, making numerous short forays along the way. Encounters between Kennedy's party and groups of aboriginals were frequent in coastal areas (Beale, 1970).

From these accounts it is clear that numerous aboriginals inhabited the coastal and island areas of Rockingham Bay, but they were less numerous away from the coast (consistent with modern interpretations of aboriginal land use patterns, eg. Maddock, 1972: 22-23). Chase and Sutton (1981) describe "..the extreme (by inland standards) sedentism.." of coastal dwelling aboriginals on Cape York, a pattern likely to be repeated on the wet tropical coast. The observations of "...large smooks..." suggests that they may have made extensive use of burning in the region. It seems likely that there is a causal relationship between the use of burning by aboriginals and the anomalous grasslands of the Bellenden Plains area (Ch 2.1.4). The timing of the burning (June) is consistent with aboriginal hunting fires rather than hot, late dry season wildfires ignited by lightning.

The following points relating to fire, and Aboriginal use of it are relevant:
(i) Lightning induced fires are very rare in this region at any time (Hamwood, pers. comm., 1992);
(ii) Both forest fires and lightning strikes in the region occur infrequently during winter (Fig. 2.3.1);
(iii) Braithwaite (1991) notes that, contrary to generally accepted ideas, ethnographic and ethnohistorical evidence show that aboriginal burning takes place at all times of the year except when the terrain is too wet to burn;
(iv) Aboriginal floodplain burning in Arnhem Land is predominantly in the May - August period (Haynes, 1985; 1991);
(v) Efforts were always made to stop fires entering closed forests (Arnhem Land; Haynes, 1985)).

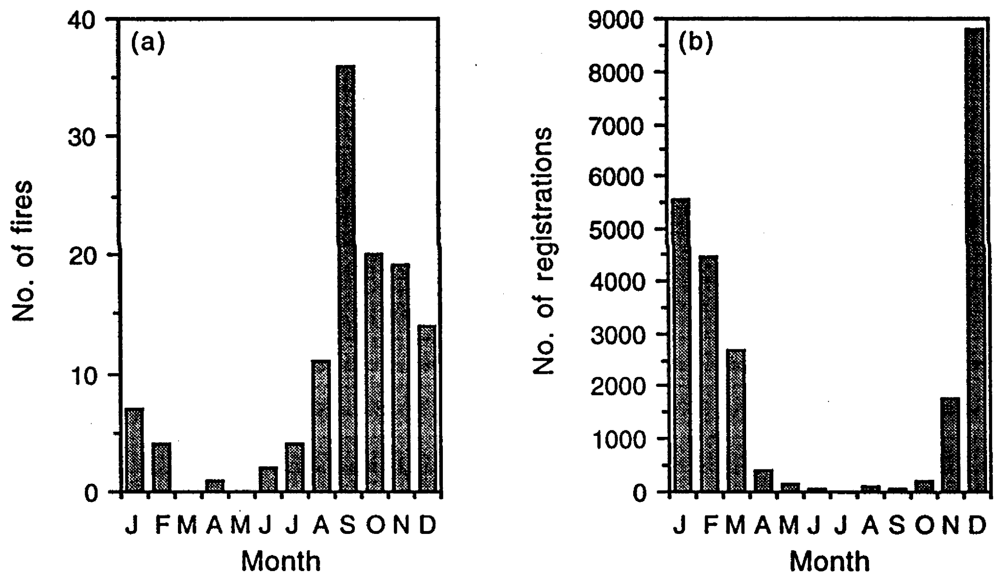


Fig. 2.3.1
Seasonal distribution of:
(a) total number of fires in or adjacent to State Forests in Cardwell Shire (unpubl. data, Queensland Forest Service; 1934 - 1992), and
(b) average number of lightning flash counter registrations at Townsville (Aust. Bur. Met. data; 1974-77, 1980-82, 1990-91).

Ethnographic evidence from the time of first European settlement shows that aboriginals did use hunting fires in the lowland wet tropics. At Herbertvale, in the Herbert River valley, Lumholz (1889: 99-100) reports such a hunt which appears to have taken place in the period July - September, 1882. Hunts were usually held in the afternoon, to allow the heavy dew to dry. The "..spot where the wallaby hunt was to take place..was a large open plain, surrounded on all sides by scrub and overgrown with high dense grass..The usual way of hunting for these animals is by setting fire to the grass." The method is as follows: "They soon separated, some of them stationing themselves on the outside of the field, while the rest remained to set fire to the grass...Soon those who had remained behind spread themselves out, set fire to the grass simultaneously at different points, and then quickly joined the rest. The dry grass rapidly blazed up, tongues of fire licked the air, dense clouds of smoke rose, and the whole landscape was soon enveloped as in a fog. .. blacks..ran about like shadows, casting their spears after the animals that fled from the flames. But though many spears whizzed through the air, and though a large field was burned, not a single wallaby was slain." (Lumholz (1889) states that the annual rainfall at Herbertvale was 90" (2 300 mm)).

Given that the rate of retreat of dry monsoon forests under a mid-dry season hunting fire regime is very slow (Bowman, 1992), it seems likely that, in the very wet climate of the Tully-Murray basin, hunting fire induced retreat of the rainforest would occur at an extremely slow rate, if at all under the present climate. Nevertheless, aboriginals have been in Australia for > 40 000 years and Kershaw's (1986) palynological data from the Atherton Tableland suggests that there may have been 26 000 years of aboriginal occupation in the region, during which grassland establishment and maintenance by burning and resulting gradual retreat of the rainforest has probably occurred.

However, unlike the dry monsoon rainforests in which very limited establishment of monsoon forest seedlings into surrounding savanna grasslands occurs even when they are unburnt (Bowman, 1992; Bowman and Fensham, 1991; Bowman and Panton, 1993), in the wet climate of the Tully-Murray basin recolonisation of fire-maintained grasslands on cessation of burning would be quite rapid. This is suggested by the rapidity of tropical vine forest recovery from cyclone damage (Webb, 1958; Unwin *et al.*, 1988; and Banfield, 1925: 1-20 for an anecdotal account and photographic record) and by observations of rainforest regeneration at sclerophyll and at grassland boundaries (House, 1986; Tracey, 1985) in northeast Queensland. A further example is reported by Gilmour *et al.* (1982) who describe a catchment on metasediments, formerly under mesophyll vine forest with a rainfall of 4 200 mm.yr^{-1}. During 1973, 67 % of this catchment was cleared, raked and partially ploughed for pasture. Economic conditions changed and no planting was carried out. By mid-1977, half of the treated catchment had been colonised by grasses and the remainder by regrowth rainforest. By 1981 the regrowth had expanded slightly, shown rapid growth and was developing the rudiments of the pre-clearing rainforest structure.

A factor which could reduce the re-establishment rate of the rainforest into the adjacent grasslands is soil degradation. The earliest descriptions of the Tully-Murray Basin (and the coastal wet tropics, generally) often refer to the common, but not universal, contrast between the rich soils of the scrub and those of the grasslands (eg. " ..there is some very good open country and rich scrubs..the scrubs being very deep and the soil remarkably rich." and "..good rich soil plains, and still richer scrub lands." Hull (1871b); "..a few thousand acres of dense jungle and rich soil suitable for tropical agriculture, .. enhanced by .. proximity to good pasture lands." Hill (1874)). There was recognition as early as 1871 that clearing of rainforest led to soil degradation ("even the rich scrub soils of Queensland can be exhausted..[and this is]..most observable in scrub farms eight or ten years in cultivation, and from which the roots have all rotted away.." (Anon., 1871)).

The soil degradation consequences of tropical rainforest conversion to pasture are widely documented with increased soil loss and stream sediment concentrations (Gilmour *et al.*, 1982) and decline in soil nutrient status and organic matter content (Charley, 1983; Potter, 1987) and acidification (Potter, 1987) being common responses.

The available evidence suggests that, prior to European settlement, the Tully-Murray basin supported a human population greater than the drier areas to the south or inland. These people probably used hunting fires extensively, principally for wallaby hunting. Over millenia, the result of these fires was the destruction of extensive tracts of lowland tropical rainforest (Type 1a - complex mesophyll vine forest), degradation of the soil (declining nutrient status through leaching and volatilisation, reduced water holding capacity, and changed soil texture) and a marked decline in species diversity in the areas burnt. This was described by Lumholz (1889: 103-104):- "..fewer birds in this open country than elsewhere in Australia.."; "Parrots were also scarce, but in the scrubs up in the mountains I saw plenty of them."; "[In].. the open country...there was but little game..[but an]..abundant harvest in the scrubs, where there is a greater variety of animal life.". By analogy with rainforest to grassland conversion, and of burned pasture elsewhere, it is likely that suspended sediment concentrations in the increased volume of runoff water would have increased. However, there remains uncertainty as to whether these grasslands were created or maintained by Aboriginal burning (Webb, 1977) and the extent to which soil drainage is a factor.

Ecosystem destruction for fun and profit?
"the hunt of the wallaby..is the sport most dear to the men"
"During the whole [wallaby] chase the women took the greatest delight in watching the sport of the men"
"though many spears whizzed through the air, and though a large field was burned, not a single wallaby was slain"
Lumholz (1889, 100-102)

2.3.1.2 Timber getting:

Walter Hill conducted expeditions to Rockingham Bay in 1862 and 1865. His report aroused the interest of cedar-getters who subsequently exploited the forests of the Herbert River valley (Birtles, 1988). Hull (1871b) suggested that "There appears to be plenty of cedar in the scrubs along the banks.." [of the New [Hull] River] and, on the Mackay [Tully] River "..nothing can surpass the richness of the scrub soil - and the banks are lined with timber of the cedar tribe." At about the same time "J.O.B." (1871) reported that "I was out from Cardwell fourteen days, and examined a deal of country and scrub,..[Cardwell, Bellenden Plains, east face of Cardwell Range, north of the Macalister [Tully] and returning to Cardwell]..but did not see a single cedar the whole trip." Dalrymple's (1874) report proclaimed the suitability of the coast between Cardwell and Cooktown for agriculture, as well as again drawing attention to timber resources. In the mid-1870s the Bloomfield, Daintree, Johnstone and Tully River valleys were subsequently "..raided ... by loggers for cedar.." (Birtles, 1988), although activity was centred largely on the Bloomfield and Daintree Rivers (Bolton, 1963:77) and Jones (1961:206) reports that the Tully and Hull Rivers were prospected in 1879 by C.D. Freshney who found "very little scrub and no cedar". By the end of that decade W. A. Tully (the Under-Secretary for Lands) reported that "We are exhausting the stock of some of the most valuable timber trees ... In some districts the cedar has disappeared, and the young trees are cut down without scruple." (Tully, 1881:145; Note: these remarks apply to rainforest areas of Queensland generally and not specifically to the Tully District). Birtles (1988) notes that Tully's attempts at forest conservation were dismissed by politicians of the day as too unpopular and cedar-getters commenced operations in the Atherton - Evelyn rainforests in the year of Tully's report. However, despite Birtles (1988) assertion that the Tully River valley was raided by loggers for cedar in the mid-1870s, it seems unlikely that any significant cedar-getting took place in the Tully catchment prior to about 1900.

A timber mill was moved from Geraldton (now Innisfail) to the Tully River in 1905, largely to service the banana industry, supplying cases and crates and timber for sampan construction. At this time timber-getting was underway in the North Hull catchment and, from 1908, logging of red cedar commenced in the Cochable Creek catchment from where logs were floated to the Tully mouth during wet seasons (Jones, 1961: 297).

2.3.1.3 Agriculture - early developments:

Agriculture commenced in the region in 1866 with the grant of a 1 280 acre lease to J.E. Davidson on the banks of the lower Murray River. Davidson's lease was severely affected by flooding. Pike (1972) reports that a monsoon flood followed by a cyclone completely destroyed the 40 acres of cane Davidson had planted in his first year, as well as half of his cattle herd. Annotations on Phillips' (1870) "Plan of J.E. Davidson's Sugar Plantation ..." indicate that, although about £ 2 000 had been expended on improvements and there were "between seventy and eighty acres of sugar cane on the ground fit to crush", nearly all of the area shown on the plan had been flooded during the year. During the January, 1870 flood, water was reported as > 2m deep at Davidson's house site and it took 5 weeks for the flood to subside (Jones, 1961:127). Davidson sold Bellenden Plains in 1871 and it was abandoned by 1874. At this time the cultivation method was "trashing" in which trash was stripped from the growing plant by hand to admit light and air, and the trash was placed between the rows to inhibit weed growth (Jones, 1961:124).

Cattle baron James Tyson took up three 2 072 ha blocks on the Tully River in 1880 with the intention of cultivating sugar cane. Two of these blocks were taken up in the names of his nephew (Hewitt) and his niece's husband (Henry) (Jones, 1961: 221-222). Tyson planted 61 ha of cane and crushing was done by hand (Henry, 1937; cited in Moore, n.d.). Tyson's properties were also used for grazing, cattle being driven overland from the south in 1882 (Jones, 1961: 226). At 30.12.1880, 24 800 ha of land in the Cardwell District was under lease, with only 61 ha cultivated (Tully, 1881: 145).

Tyson was, like many others, convinced that a source of cheap, black labour was essential for viability of sugar cane production. The South Pacific labour trade (kanaka-trade, blackbirding) had commenced in Australia in 1847 with the importation to southeast New South Wales of 70 Lifou, Ouvea and Tanna Islanders by Benjamin Boyd. In that year, Boyd imported 140 kanakas (Holthouse, 1969: 14-16). In Queensland, the labour trade was initiated in August, 1863 by the Sydney businessman Robert Towns for cotton and subsequently sugar cane cultivation in southeast Queensland (Docker, 1970: 11). Davidson had 20 kanakas at Bellenden Plains and subsequently Tyson and Henry had kanakas on their properties, Tyson having about 40 (Henry, 1937; cited in Moore, n.d.). When Samuel Griffith's party won government, legislation (Abolition of Island Labour Act, 1885) was passed to wind up the labour trade by December, 1890. In response, Tyson abandoned the property, machinery and schooner, although Jones (1961:232) suggests that poor sugar prices may have been a factor in this action. Recruiting only slowed down in 1891-2 and, due to economic pressures, was at full swing again by 1893 (Corris, 1973: xx-xxi). Griffith repealed the 1885 Act with the "Pacific Island Labourers Act, 1892". The labour trade ceased, and deportation of most of the 2 500 remaining kanaks (Moore, 1990) took place after Australian federation in 1901. Legislation for the "Regulation, Restriction and Prohibition of the Introduction of Labourers from the Pacific Islands" was assented to on 17.12.1901 (Docker, 1970: 260).

With Tyson's abandonment of cane growing, there was no sugar mill or real prospect of one in the Tully district so, although land holdings were being taken up, development of cane growing was severely retarded. In fact, Jones (1961:274) reports that, in 1898, about 7 500 ha of land was held along the Tully River, largely by Tyson, but was unoccupied.

2.3.1.4 *Banana growing:*

The next important land use change in the area after the collapse of Tyson's venture was the arrival of Chinese gardeners and horticulturists, largely between 1901 and 1903 (Bolton, 1963: 226). Their influx was a consequence of the collapse of the gold diggings to the northwest, 'exhaustion of the soil' in areas where they had previously cultivated bananas and little competition for land in the absence of a sugar mill in the Tully district. The major environmental impacts of the Chinese presence were land clearing for banana growing along the banks of the lower Tully, and clearing of the river banks for loading facilities, with consequent increased sediment yield a likely result. Banana farms were generally 4 ha to 8 ha in area and Chinese growers kept the entire area completely free of all weeds and grass. The lower Tully was, then as now, navigable only for shallow draft vessels and loading took place from numerous small landing stages for lightering to the river mouth. Banana cultivation was also carried out by kanakas and, later, by whites. The industry reached its peak in the area during the period 1905-1908 (Jones 1961:290) and collapsed with the development of competitive banana growing closer to Brisbane, the disruption of shipping services during World War I (Bolton, 1963:226) and the coal strike of 1916 (Jones, 1961:306).

After the collapse of banana production in 1915 (from 460 ha to 5 ha a year later) there was little banana cultivation until 1958. Although there were two expansions in the area cultivated for banana production to about 100 ha in 1930 and in 1945, in the pre-war period about 15-25 ha of banana cultivation was the norm, and post-war it was about 20-25 ha. From 1958 the area under banana cultivation increased steadily to a peak of 815 ha in 1972 (Fig. 2.3.2), followed by a slump to 673 ha in the following year and a subsequent steady increase to 1 600 ha in 1984.

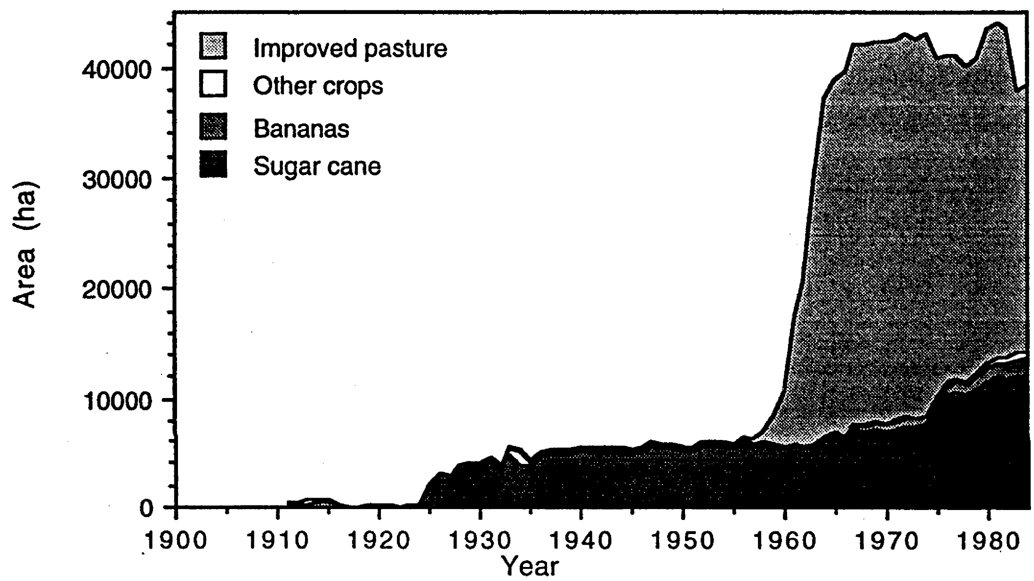


Fig. 2.3.2
Time series of land use change in the Tully River catchment. (based on ABS data)

Local growers report that the area has found favour for banana cultivation because of the availability of land (ie. less pressure from alternative uses, as in northeast New South Wales), less incidence of crop disease, level terrain is easier to work than is the case in some other areas (eg. northern New South Wales) and it is possible to get back on the land much sooner after rain than in some other areas (eg. the lower Burdekin; 2 days instead of one week). Disadvantages of the Tully area are that bananas "do poorly on the red granite soils", requiring well drained alluvial soils. Drainage is often enhanced by pushing top soil into ridges and planting into the ridges.

The need for good drainage and large quantities of water means that sites adjacent to the river are preferred for banana cultivation and irrigation is extensively practiced. In 1983-1984, 1 279 ha of land in the Cardwell Shire was irrigated of which 70 % was applied to fruit. By 1986-1987 the total area had increased to 1 800 ha of which about 90 % was applied to fruit crops, principally bananas (ABS data).

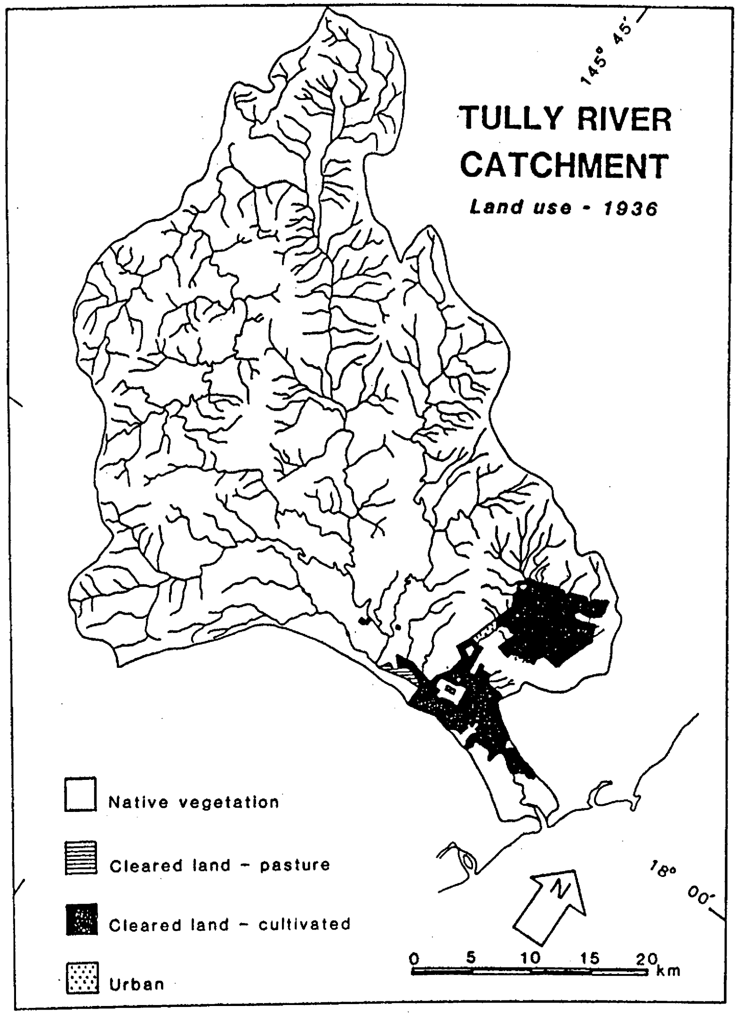
2.3.1.5 *Establishment of the Tully Mill:*

Significant changes took place in the lower Tully catchment in the mid-1920s. The railway extension from Townsville to Cairns was surveyed through the Tully - Murray area between October, 1919 and October, 1920 (unpubl. surveyors note books) and railway construction reached the area, completing the link, in December, 1924. After many years of lobbying by the increasing population of the Tully-Banyan area, the new Sugar Works Act (1922) was passed authorising construction of the Tully Mill. Crushing commenced on 5.11.1925. The combination of the opening of the mill and the completion of the railway was the trigger for a major expansion of the embryo sugar growing industry. The new town of Tully was surveyed in April, 1924 and gazetted on 24.1.1925, after which time the township of Banyan, on the east bank of Banyan Creek, was gradually abandoned. Banyan had been so overcrowded that half of its residents lived in eighty dwellings on the road (Jones, 1961: 340-341).

These developments paved the way for a major expansion of cane growing in the Tully district. The initial surge in development took place immediately prior to and just after the mill opening. Associated with this agricultural expansion was an increase in unsealed road construction and livestock numbers, both of which would be expected to result in increased sediment yield. Photographs of the time show that most of the area of both Banyan and Tully, apart from that covered by buildings, was bare soil with no vegetative cover. Cane growing at this time was concentrated in the Banyan Creek catchment (Fig. 2.3.3).

2.3.1.6 *Sugar cane growing:*

Prior to construction of the Tully Mill the area under sugar cane had steadily increased to 216 ha by 1924. By 1928 the area under cane had increased to 3 893 ha (Fig. 2.3.2), an annual increment of 919 ha. During this period, most cane supplied to the Tully Mill came from the Feluga and Midgenoo areas (Banyan catchment), Euramo, Silky Oak, Syndicate and Lower Tully (on the Tully alluvial plain in the same general area as most of the Chinese banana production had been) and from El Arish (Jones, 1961:351) in the Maria Creek



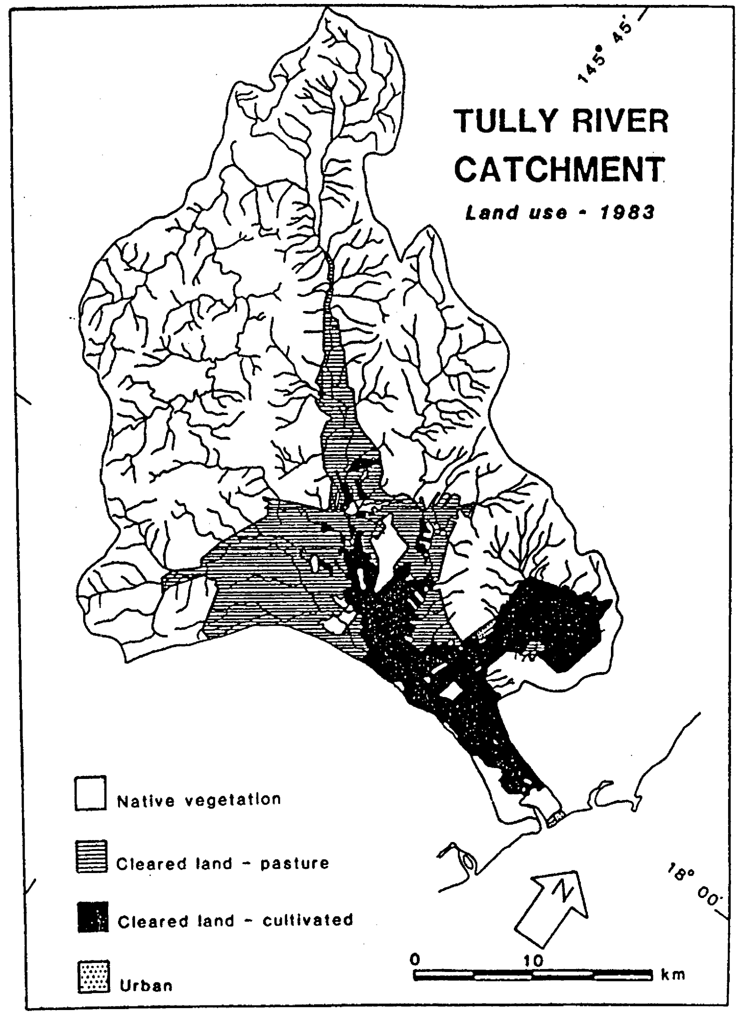


Fig. 2.3.3
Generalised land use maps for the Tully River catchment for 1936 and 1983 (mapped from vertical air photography).

catchment on the northern side of the Walter Hill Range. In the period 1928 to 1956 the area cultivated for cane increased at an average rate of 73 ha.yr^{-1} to 5 941 ha. A decline to 5 284 ha took place until 1962, after which there was a continued increase until 1981 (at 353 ha.yr^{-1}). The peak rate of increase (1 390 ha.yr^{-1}) took place between 1974 and 1976.

The crop growth cycle for sugar cane in northeast Queensland is based on planting in the period March to September and harvesting in the following June - December period. Two to three rattoon crops, from shoots from the previous crop, are harvested in following years. Subsequently, the field may be fallowed or a legume may be cultivated. Plant growth is at a maximum during the monsoon period when temperatures and rainfall are high. In the winter and spring months, temperatures and rainfall are lower, crop growth declines and sugar content increases. The relationship of climatic conditions, crop growth, sugar content and harvest time is critical to the yield of the crop.

Particularly since the 1940s, burning prior to cane harvesting has been the norm, superceding the much more labour intensive "trashing" method. For manually harvested cane, burning has the advantage of removing vermin (eg. snakes) from the crop and makes harvesting and milling more efficient. For mechanical harvesting, as all Australian cane now is, burning removes the trash which tends to impede harvesting and milling. Adoption of both burning and mechanical harvesting and loading were accelerated by labour shortages in the 1940s and 1950s. Mechanical loading was introduced in 1955 and the percentage of the crop mechanically harvested increased from 8 to 99 % in the decade 1962 - 1972 (Kingston *et al.*, 1991).

More recent concern with loss of nutrients during the cane firing process (particularly nitrogen) and high soil erosion rates (with accompanying nutrient losses) has prompted investigation of minimal tillage practices for canelands. Substantial reductions in the very high soil loss rates from canefields have been achieved on experimental plots (Fig. 2.3.4) using these techniques. Additional benefits of green cane harvesting and trash retention include increased yield, delayed and decreased runoff, increased infiltration and soil water storage, reduced weed control costs (Page *et al.*, 1986) as well as reduced fertiliser loss and tillage costs, increased soil organic matter and root development, and safer machinery operation (Capelin and Prove, 1983). Disadvantages include the need for some chemical weed control, increased fire hazard, a requirement for more expensive fertilisers to avoid volatilisation, and uncertainty as to the long term effect on pests and disease (Capelin and Prove, 1983).

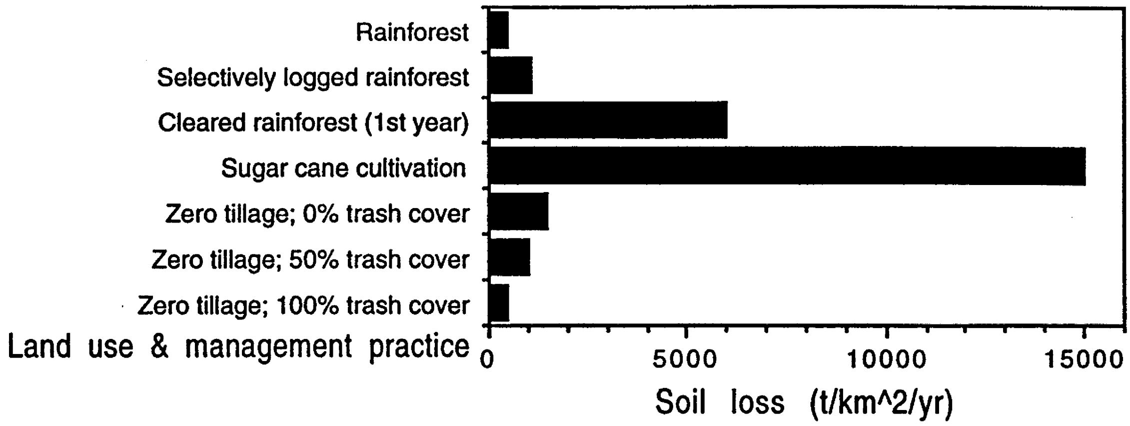


Fig. 2.3.4
Soil loss in relation to land use and management practice in the North Queensland wet tropics (data from Prove and Hicks, 1991).

Early adoption of green cane harvesting was limited by the unavailability of suitable harvesters (the first commercial green cane harvester was introduced in 1976 (Ridge and Dick, 1989)) and the inexperience of growers in dealing with the very high volume of crop residues involved (Fuelling *et al.* 1978; Ridge *et al.*, 1979). Although adoption of these practices has been steadily increasing, there is a high degree of variability between the various mill areas. As at 1990, canegrowers supplying the Tully mill had the lowest rate of adoption of any of the North Queensland mill areas (Fig. 2.3.5).

Most fertiliser application takes place during the dry part of the year from April to December (Kuhn, 1991). Application at this time minimises nutrient loss by leaching (N) and by adsorbtion on eroded soil particles (P). The changing tillage practices have also resulted in a change in fertiliser practice, with a trend to those fertilisers which can be applied to the soil surface without soil disturbance (Kuhn, 1991). A further complexity in these changes to land management practices is that, although the shift from conventional tillage to zero tillage and green cane harvesting results in decreased soil loss, it also results in increased exchange capacity and specific surface area. It follows that, given smaller particle sizes, a greater proportion of eroded soil will be transported a greater distance and will also have the capacity to transport a greater nutrient load (Prove and Hicks, 1991). However, the net effect of increased specific surface area and decreased suspended sediment concentration is not established.

The cropping cycle is important in relation to soil erosion. Crops planted early have sufficient growth by the onset of the wet season to provide reasonable ground cover. This is also the case for rattoons from crops harvested early. Growth from late planted or rattooned crops is generally insufficient to provide good ground cover until late in the wet season, thereby leaving the soil vulnerable to erosion until about February - April (Capelin and Prove, 1983). On the other hand, Prove *et. al.* (1986) suggest that full canopy cover is not reached until February - March, irrespective of the time (between July and November) of previous harvesting. It is during the early monsoon season, when rainfall intensity and erosivity is high (Fig. 2.1.13) but groundcover in sugar cane crops is low, that the soil erosion hazard in canelands is greatest. Capelin and Prove (1983) suggest that the period of greatest erosion hazard is September - October (thunderstorm activity) and December - April. Prove *et. al.* (1986) regard the hazard period as October - April. Green cane harvesting and trash retention act to reduce the erosion hazard during this critical period.

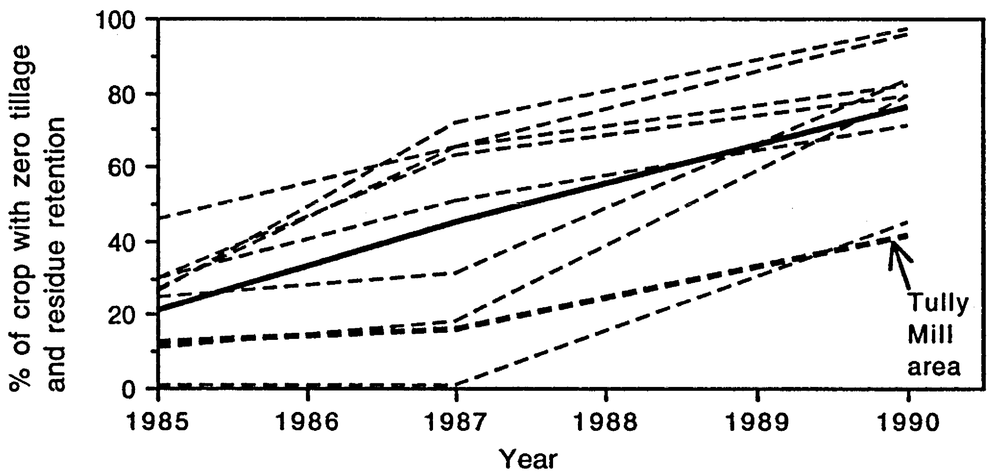


Fig. 2.3.5
Adoption of green cane harvesting practices for mill areas in the North Queensland wet tropics - 16°27' to 18°45'S (- - - individual mill areas; - - - Tully Mill area; — regional mean; data from Prove and Hicks, 1991).

2.3.1.6 *Beef cattle fattening:*

A meatworks commenced operations at Five Mile Creek, near Cardwell, in 1895 (Jones, 1961:269). However, the timing was unfortunate as the tick plague which had been destroying large numbers of stock across northern Queensland since 1891 reached the coastal areas around Cardwell in 1896. Livestock were decimated and the industry went into decline.

Although cattle numbers gradually increased after the tick plague, the major development in this industry was initiated by Brice Henry's experiments on cattle fattening using improved pastures. He planted his first 80 ha in January, 1936 and by 1938 had 1 200 ha of improved pasture (Jones, 1961:386,392). Although the research program ceased soon after his death in 1940, he had been able to demonstrate the viability of cattle fattening on improved pasture in the coastal wet tropics. A brief review of the Tully coastal pasture experiments (Bullock, 1938) outlines their results and their global marketing context.

Eventual establishment of the Tully River Station as a major cattle fattening operation on improved coastal pastures can be seen as an example of the politically, economically and agronomically contentious schemes to develop northern Australia which were floated in the 1950s and 1960s. Other examples include the Ord River Scheme in Western Australia and the Humpty Doo project in the Northern Territory. A survey of the coastal lands in North Queensland suitable for cattle fattening was undertaken in 1961 following a brief from the Queensland Minister for Public Lands and Irrigation. The investigating committee found that, in the lower Tully region, there were 2 500 ha of vacant Crown land, 7 300 ha of Timber Reserve and 6 000 ha of substantially unimproved freehold or leasehold land (66 % rainforest and the remainder "plain country") suitable for settlement as cattle fattening properties (Sloan *et al.*, 1962). About 21 300 ha was freeholded to the North American King Ranch organisation to form the Tully River Station.

Land clearing took place in the early 1960s and was accompanied by no erosion prevention or sediment detention works (Luck, 1987: pers. comm.). Land clearing was more or less continuous during this period and no attempt was made to limit soil exposure to months of lower rainfall intensity and runoff. Apparently this was, at least in part, a result of contract conditions which required clearing within a specified period. As a result, much of the millable timber could not be removed before pushing, windrowing and burning, which was the basis of some of the local controversy which surrounded the project. The pattern of rainfall intensity (calculated as rainfall.rainday^{-1}) during the period of clearing is shown in Fig. 2.3.6 and shows that there were two months during this period (December, 1964 and March, 1967) when rainfall intensity was much higher than the longterm mean. High rates of soil erosion and sediment discharge to Rockingham Bay during this period are likely.

The land cleared included significant areas of rainforest on which the cost of improved pasture establishment was about 1.8 times that for the grasslands (Sloan *et al.*, 1962). During the period 1967 to 1975 bulldozing windrows for burning was carried out. Windrows were often established in drainage lines and subsequently impeded drainage and acted as silt traps. Growth of stands of *Melaleuca*, in areas in which they had not previously grown, is evidence of the effect on drainage of this practice (Luck, 1987: pers. comm.).

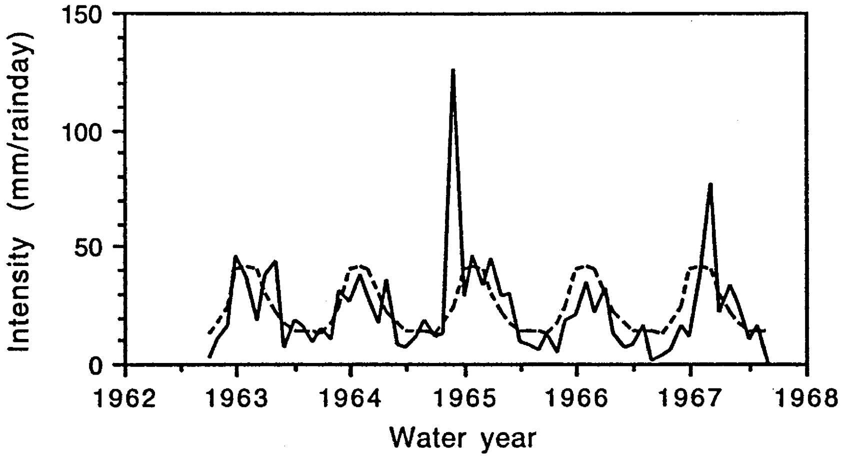


Fig. 2.3.6
Variation in rainfall intensity during the period of clearing for Tully River Station (—— calculated intensity; ----- average intensity; 1925-1991).

Seeding for improved pasture was carried out by aerial sowing. In the period post-1975 about 400 $ha.yr^{-1}$ was ploughed and sown where the original aerial sowing was unsuccessful (Luck, 1987: pers. comm.).

As a result of changing boundaries of the spatial units used in the agricultural census and changing categories of census data collection, it is difficult to compile a time series of pasture area in the Tully catchment. Fig. 2.3.2 presents a best-estimate based on ABS data and inferences from historical sources. The pattern is clearly dominated by the establishment of Tully River Station which resulted in a massive increase in the area of improved pasture and a decline in the area of native pasture. The increase in stock numbers lagged pasture improvement by about six years, but eventually resulted in a peak stocking rate of 1.4 $beasts.ha^{-1}$ in 1976, compared with only 0.25 $.ha^{-1}$ on predominantly native pastures in 1960 (and 3 $.ha^{-1}$ on Henry's experimental pastures in 1938 (Jones, 1961: 390)). The pasture area peaked at 35 000 ha in the mid-1970s and then underwent a slight decline concurrent with the expansion of sugar cane and banana growing in that decade. The decline in stock numbers appears to be a consequence of both the decrease in the area of pasture, associated with increased banana and cane growing areas, and some reduction of stocking rates.

Dairying: In 1954 the Maalan Group Settlement was established, largely for dairying, at the southern end of the Atherton Tableland (Frawley, 1987), previously a prolific timber producing area. Of the 22 km^2 in the settlement area only 3 km^2 are in the Tully catchment, in the headwaters of Cochable Creek. Pasture management early in the scheme may have resulted in high erosion rates. Use of frost- and fire-susceptible molasses grass (*Melinis minutifloria*), a summer grass which died off severely in winter, could result in no pasture at all if there was frost or fire damage (Frawley, 1987). Subsequent pasture selection and use of fertiliser have improved the ground cover quality. However, given the small area involved, its remoteness from the Tully mouth and the fact that it is on the most level terrain in the Cochable Creek catchment it is unlikely that land use change in the Maalan area has had any significant effect on water quality in the lower reaches of the Tully catchment.

<u>2.3.2 *Agricultural inputs:*</u>

Although the early history of fertiliser use in North Queensland is not documented, Pulsford (1991) suggests that little fertiliser was applied in the late nineteenth century, although a programme of field trials was initiated by the new Bureau of Sugar Experiment Stations at the turn of the century. Relatively little fertiliser was applied to crops or pasture until the mid-1950s.

At the time fertiliser inputs data were first collected by the Australian Bureau of Statistics (1945) the total application in the Cardwell Shire was 1 420 t (Fig. 2.3.7), of which 96.5 % was for sugar cane cultivation. ABS data show that fertiliser was not applied to pastures until 1958, although it seems likely that some fertiliser was used on Henry's pasture trials in the 1930s. In the period 1950 - 1962 the rate was fairly consistent at about 2 500 - 3 500 $t.yr^{-1}$. Fertiliser application increased steadily through the 1960s and 1970s to rates of 12 000 - 14 000 $t.yr^{-1}$ during the 1980s.

Reconstructions of land use and agricultural inputs are limited by the availability of data, the best published source of which is the annual Agricultural Census of the Australian Bureau of Statistics. During the late 1970s and the 1980s there has been a considerable contraction of the data available from this source.

In the case of fertiliser inputs, the relationship between specific land uses and the quantity of fertiliser applied has been ascertained by three different questions during the 1980s:

i. area fertilised and quantity of fertiliser used in 12 crop classes -
1980-81, 1984-85, 1987-88.

ii. area fertilised and quantity of fertiliser used in 4 crop classes (pastures, wheat, sugar cane, other) -
1982-83, 1983-84, 1985-86, 1986-87, 1988-89, 1989-90

iii. area fertilised and quantity of fertiliser used in 1 crop class -
1990-91, 1991-92.

Similarly, quantities of fertiliser were itemised by 5 fertiliser types prior to and including 1989-90, but since that time only the total quantity has been ascertained.

As a result of these changes, there is a decline in the quality of the data presented in Figs. 2.3.7 and 2.3.8 in the recent part of the record.

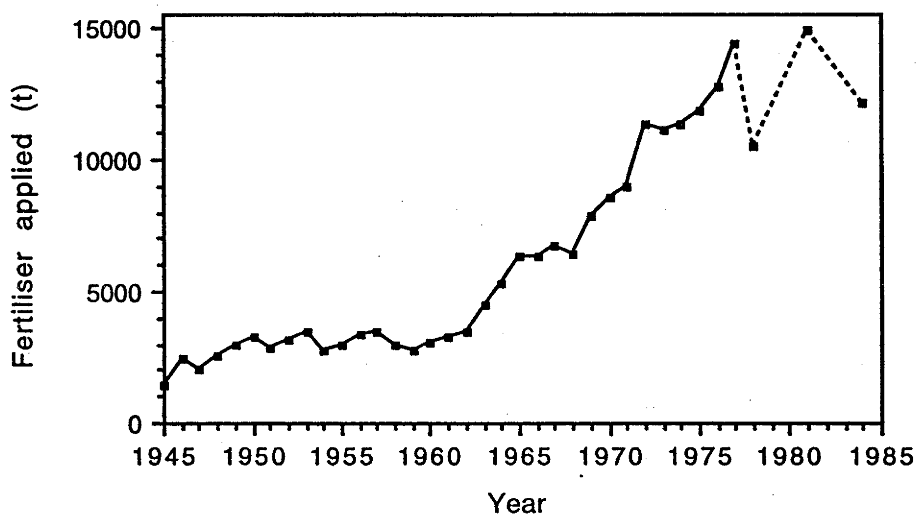


Fig. 2.3.7
Total fertiliser application in Cardwell Shire (ABS data).

For the period of record, fertiliser application rates for all crops have increased. However, different crops exhibit markedly different temporal patterns. In 1945 the rate of fertiliser application to bananas (0.34 $t.ha^{-1}$) was greater than that for cane (0.28 $t.ha^{-1}$). Subsequently, the rate of application to bananas declined to 0.0 in 1951, whereas for cane it doubled to 0.63 $t.ha^{-1}$ in 1950 (Fig. 2.3.8). Application rates generally increased until 1973, after which some decline occurred, largely due to economic circumstances brought about by depressed sugar prices. Pulsford (1991) suggests that sugar price is the most important determinant of the fertiliser application rate to sugar cane crops, although declining nutrient status of soils is likely to be important in the long term trend.

By the mid-1970s expansion of the banana growing areas had occurred and their fertiliser application rates, although lower than those for sugar before 1964, rapidly increased until, in the 1980s, the average rate of fertiliser application to bananas was about 2.5 times as great as for sugar.

Rates of fertiliser application to vegetables have been more variable than for bananas and sugar cane, although an increasing trend through the 1970s has resulted in the present rate being greater than that for sugar cane.

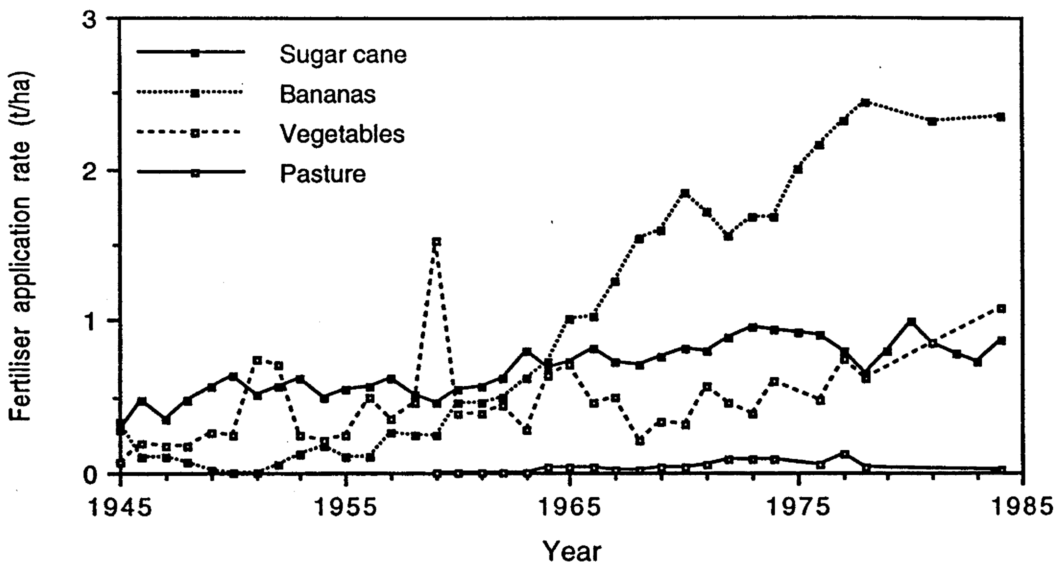


Fig. 2.3.8
Time series of fertiliser application rate by land use class (based on ABS data).

The proportion of total fertiliser inputs applied to the various land uses has changed considerably over the period of record. In 1959 sugar growers used 95 % of the fertiliser applied, but this declined to a minimum of 58 % in 1972 at which time 29 % was applied to pasture (Fig. 2.3.9). During the late 1960s and early 1970s about 20 % of fertiliser was applied to improved pasture. This was the post-clearing establishment phase of the Tully River Station. Since that time application rates to pasture have declined markedly. In the 1980s, fertiliser application is on a maintenance basis on a rotating cycle of application which takes approximately six years for completion. The cycle is based on an application rate of 9 cwt/ac. (1.13 t.ha^{-1}) (Luck, 1987: pers. comm.), so that in any given year only about 17 % of the 21 000 ha will be fertilised, but the application rate for the area actually fertilised is comparable with that for canelands. Small quantities of sodium molybdate, zinc and copper sulphate are also applied to Tully River Station pastures, the latter application restricted to upland areas. About 60 % of the pasture land in the Tully catchment lies within the Tully River Station.

Fertiliser application was a response to demonstrated soil nutrient deficiencies, particularly of P but deficiencies of Cu, Zn and K were also widespread (Teitzel and Bruce, 1971). Pastures on granitic soils, for example, yielded large increases in plant growth from small P application rates, although 'optimum responses' occurred at 0.05-0.1 t.ha^{-1} (Teitzel and Bruce, 1971). Assuming a P content in commercially available fertilisers of about 10%, this represents an application rate of 0.5 - 1.0 t.ha^{-1}, about three times the average rate actually applied to pastures, taking account of the rotation of application.

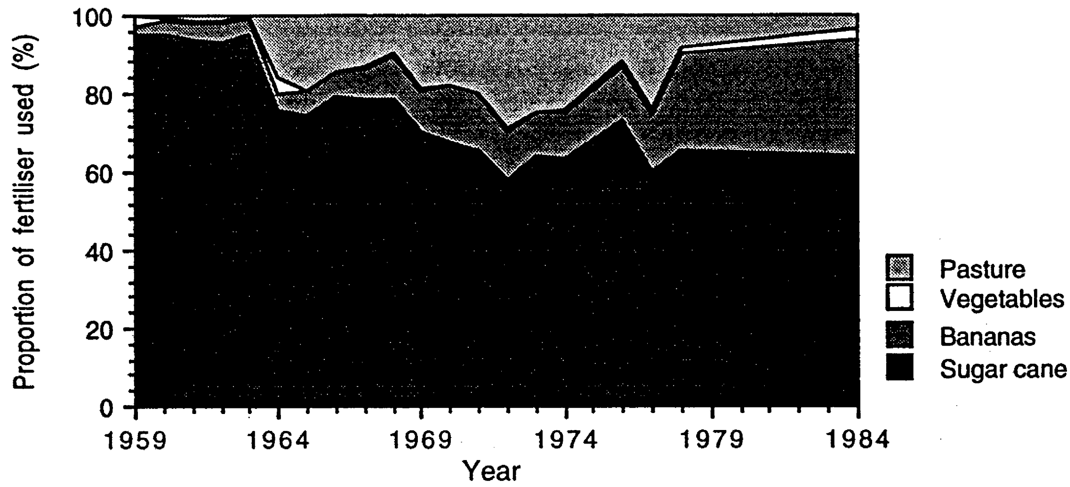


Fig. 2.3.9
Relative proportions of fertiliser applied in the major land use classes in the study area (based on ABS data).

The rapid increase in both the cropping area and fertiliser application rate for bananas has resulted in this crop accounting for 20 - 25 % of fertiliser applied through the late 1970s and 1980s (and steadily increasing), with sugar cane accounting for about 65 % and decreasing.

Change in demand for different fertiliser products reflects changing knowledge of plant nutrition, soil properties, manufacturing processes and storage and transport costs. Over the last 25 years fertiliser products with relatively low nutrient concentrations (sulphate of ammonia, aqua ammonia and single superphosphate) have been replaced by those with higher nutrient concentrations such as urea and di-ammonium phosphate (Table 2.3.1). A strong trend to blended fertilisers is evident in the north Queensland fertiliser market (Kuhn, 1991).

Product	Nitrogen (%)	Phosphorus (%)	
Ammonium sulphate	20.2		
Aqua ammonia	20.5		
Superphosphate		8.8	
Urea	46.0		
Di-ammonium phosphate		18.0	10.0

Table 2.3.1
Nutrient content of selected fertilisers (from Kuhn, 1991).

The reliability of the ABS fertiliser application statistics has been questioned by Pulsford (1991) who gives three examples in which ABS superphosphate estimates are greater by factors of 1.4, 4.0 and 6.5 than industry estimates. It should be noted that the two greater figures are for single years whereas the lesser one is based on cumulative data over 11 years and it is possible that discrepancies in a single year may even out over a longer time frame.

Pulsford (1993; pers. comm.) offers an alternative explanation. The ABS agricultural census form asks for 'Area fertilised', then, under the heading ' Quantity and type of fertiliser used' asks for 'Superphosphate', 'Urea', 'Sulphate of ammonia', 'Other straight nitrogenous types', and 'Other artificial fertilisers' (other type categories are used, however all list superphosphate first). Pulsford suggests that the ABS 'area fertilised' data is reasonably accurate, but when respondents complete the first 'quantity and type' column ('Superphosphate') many put all their fertiliser usage into that column and neglect the other columns. Consequently, superphosphate use is overstated in the ABS data but total fertiliser use (on which Fig. 2.3.7, 2.3.8 and 2.3.9 are based) is consistent with industry sales figures and quite accurate (Pulsford, 1993; pers. comm.). Fig. 2.3.10 shows the pattern of N and P use in the Tully-Murray basin based on Pulsford's data. These data are corrected for the effect of changing analysis of the fertiliser used. The very high application rate for P in 1980 is the result of a large quantity of rock phosphate (loader dust) being marketed at very low prices. The application was to Tully River Station (Pulsford, 1993; pers. comm.) and is not reflected in the ABS data. The marked increase in N application since 1985 is due to the expansion of banana growing.

The overall pattern of fertiliser application is one of increasing rates of application of higher nutrient concentration fertiliser on an increased area of crop and pasture with an increased proportion of cultivated land under crops with higher fertiliser demands.

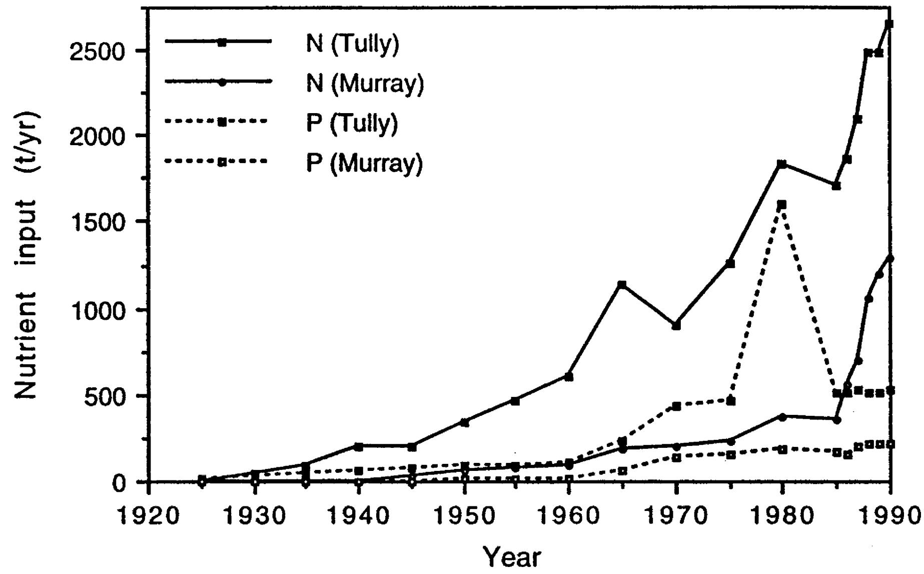


Fig. 2.3.10
Time series of nitrogen and phosphorus inputs to the Tully and Murray River catchments based on industry sales data (Pulsford, 1993; pers. comm.).

2.3.3 *Hydrological effects of land use change:*

The major hydrological impacts of land use change in the Tully River catchment relate to the effects of clearing for agriculture and pasture, as well as clearing stream bank vegetation, drainage works and construction of Koombooloomba Dam and associated diversion works.

Development of a hydro-electric scheme on the Tully River had often been suggested prior to the eventual commencement of construction. Former State Premier E. G. Theodore had first visited the Tully Falls site to evaluate the scheme in 1925 and Tasmanian hydro-engineers inspected the site in 1928 (Jones, 1961:347-348). Survey work was undertaken from the late-1940s and construction of the scheme was authorised in 1950. The scheme required construction and upgrading of access roads, a new bridge across the Tully River and establishment of a village (Cardstone).

The hydro-electric scheme entailed construction of a 180 x 10^6 m^3 reservoir, a 0.725 x 10^6 m^3 diversion weir, a 1 700 m tunnel with a head of 450 m, a power station and switch yard (Shepherd *et al.* , 1959). The scheme was completed in September, 1960, with subsequent increases in generating capacity scheduled. Addition of an inflatable "Fabridam" in 1965 increased reservoir capacity by about 10 % (Hausler, 1991). Present generating capacity is 72 Mw.

Mean annual rainfall for the Koombooloomba Dam catchment is 2 610 mm, of which about 83% is runoff (as estimated by QWRC; 1919-1969 and

1949-1964 data for rainfall and streamflow, respectively (Bonell, 1988)). In the period 1964 - 1986, the Fabridam was overtopped in only 55 % of years (QWRC, unpubl. data). Because of the relatively low rainfall in this part of the Tully catchment, and the reservoir catchment (164 km^2) comprising only 10 % of the catchment area of the Tully River, the Tully Falls scheme has only a minor effect on the hydrology of the catchment and provides very limited flood mitigation (Anon., 1977). The dam may also have caused a slight reduction to downstream sediment loads, given an estimated trap efficiency of c. 88 % using the Brune's curve method (Brune, 1953), although associated construction works and infrastructure are likely to more than compensate for this effect.

Drainage of agricultural land commenced in the study area with the improvements made to J. E. Davidson's property from 1866 (Eden, 1872; 290). Within the Tully, Murray and Hull catchments, at 1978, there was about 105 km of drains, of which 7 % was through pasture lands, 8 % through banana farms and most of the remainder through caneland. Not all of the drains are entirely artificial. Many follow prior stream lines or drainage depressions which have been excavated and cleared of vegetation for increased hydraulic efficiency.

Flooding has been a significant constraint on sugar cane production in the Tully-Murray basin since Davidson planted his first crop in 1866. Eden (1872; 290) discusses flooding at Bellenden Plains and describes "..a Christmas Day, which, with the two following he [Davidson] spent at the top of a tree, his two men being in one near him."). Flooding can result in marked decreases in cane yield (Fig. 2.3.11), the severity of the impact being dependent on the time of occurrence (age of the crop) and the depth and duration of inundation. Little damage results from a flood of < 3 days duration, and damage increases with duration. Consequently, one of the main management responses to flood hazard has been attempts to minimise duration. Construction of drains is one part of this. Works on the Tully stream channel proper have also been undertaken and further works recommended (see below). On Tully River Station land clearing, ploughing and seeding took place in the period 1963 to 1967 and rates of fertiliser application were at their maximum in the mid-1970s with a subsequent decline. During the 1980s the major land management program on this property has been drainage works (Luck, 1987: pers. comm.). These works have been, in part, restorative as, at the time of clearing, much of the forest which was cleared was pushed into drainage lines. In addition to clearing out this debris, however, deliberate action is also taken to improve hydraulic efficiency and some new channels have been excavated, often too small to be reliably detected on small scale air photos. Landholders in the lower Murray catchment attribute increased runoff and flooding to the drainage works and land clearing upstream (Anon., 1977).

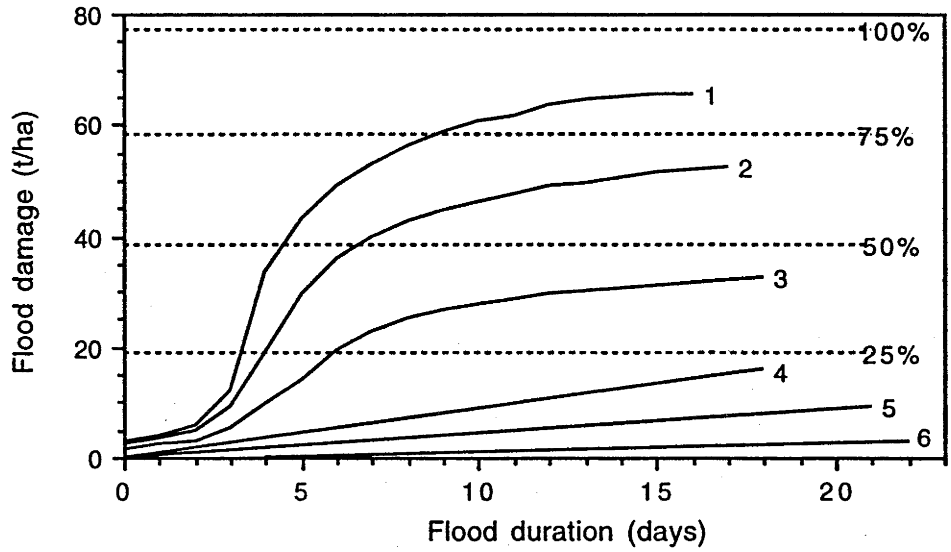


Fig. 2.3.11
Estimates of flood damage (as loss of crop) to sugar cane crops with flood duration, water depth and time of flood. (Curve 1 - 1m (Nov), 1.3-1.6m (Dec); 2 - 1-1.3m (Dec), 1.3-1.6m (Jan); 3 - 0.6m (Dec), 1-1.3m (Jan), 1.3-1.6m (Feb); 4 - 0.3-0.6m (Jan), 0.6-1.0m (Feb), 1.3m (Mar), 1.6m (April); 5 - 0.3m (Jan), 0.3-0.6m (Feb), 1.0m (Mar); 6 - 0.0-0.3m (Feb), 0.3m (Mar); Dashed lines are percentages of mean yield for cane delivered to Tully Mill for the years 1965 - 1974; Data from Anon., 1977; Moore, n.d.).

Sand and gravel extracted from the stream bed is used for construction purposes and also by farmers for flood control works and to raise the level of their land relative to flood heights. Extraction sites are often located on inside bends with the intention of reducing erosion where the outside bank is subject to severe erosion.

Modifications to the Tully River stream channel include meander cutoff, flood gate construction on minor tributaries, clearing of stream bank vegetation and mining of stream bed sediments. Engineering works associated with flood mitigation, drainage improvement and streambank erosion mitigation have been the subject of considerable debate locally. Numerous engineering works have been advocated (see Anon., 1977) many of which are still the subject of debate. These include a variety of drainage diversions affecting the Tully and Murray Rivers and Bedford, Corduroy, Lagoon and Weiss Creeks, 'improvement' of stream channels, construction of floodgates on tributary streams and drains, construction of levees, sand extraction and meander cutoff. Unauthorised construction of levee banks and drains and extensive landfilling on the Tully River alluvial plain result in the likelihood of higher flood peaks and more widespread flooding (Keane, 1987: pers. comm.).

Although there is little direct evidence of the effect of catchment modifications in the Tully basin on hydrograph characteristics, anecdotal evidence and conclusions drawn by analogy with similar land use changes elsewhere suggest that the peak discharges during flood events would have increased and the event duration would have decreased. Consequently, it could be inferred that (given unchanged climatic conditions) the frequency of floodwaters reaching the fringing reefs of the offshore islands would have increased. Decreased flood peak duration would result in the sediment laden river waters being less persistent in Rockingham Bay. However, it must be recognised that little of the foregoing is based on hard data. Cassells *et al.* (1985) have noted the lack of impact on floodflow by clearing in high rainfall catchments in the region and attribute this to an intensely active hydrological regime with widespread saturation overland flow, even under natural conditions, leaving little potential for land use change to induce increased surface runoff.

2.3.4 *Island land use:*

It is clear from accounts of the early navigators and explorers that the islands of Rockingham Bay were occupied by quite large numbers of aboriginals. It is unclear what their impact on the vegetation of the islands was or the nature of changes since their departure.

The most intensive land use on any of the Rockingham Bay islands is on Dunk Island. Although Dunk was conditionally recommended as a naval depot (Dalrymple, 1874), it was unoccupied until E.J. Banfield settled there in 1896. Apart from his vegetable gardens, Banfield's interest in the island was as an amateur naturalist and very little alteration of the natural environment resulted from his tenure. Banfield died in June, 1923 after which his wife left the island, dying in Brisbane in 1933. On her death the island changed hands a number of times. In 1936 a tourist resort was opened and land was cleared for an airstrip 300 x 40 m (Jones, 1961: 381). Since that time there has been a gradual expansion of the resort area until much of the sandspit area and a small area of the southwest foothills of the island have been cleared or the vegetation extensively modified, largely for the (now sealed) airstrip and the resort complex. About 95 % of Dunk Island is National Park (NP 382) as are the adjacent Purtaboi, Mung-um-Gnackum and Kumboola Islands (NP 493, NP 494, NP 418, respectively).

On Bedarra Island there are two very small tourist resorts, largely on the leeward sandspit and bayhead beaches, and a private dwelling, the rest of the island remaining uncleared. There are two private dwellings on Timana Island, changes to the vegetation being limited largely to the leeward sandspit. Timana Island is privately owned. Wheeler, Coomb, Smith, Bowden and Hudson Islands are entirely National Parks, gazetted in 1936, with no development (NP 384, 385, 386, 387, 388, respectively). At the turn of the century unsuccessful attempts were made to run sheep on Goold Island (Jones, 1961:302-303), but there has been little activity there since that time. Goold Island is now National Park (NP 389; gazetted in 1936). Hill (1874: 666) recommended that the islands of Rockingham Bay be used as acclimatization areas with Brook having food and good shelter for game birds. Subsequently, guinea fowl were introduced but probably ended up "..in some blackfellow's cooking pot.." (Jones, 1961:194). There were some fishermen's huts on Brook Island in the late 19th century (Jones, 1961:276) and during WWII, Brook Islands were used extensively for chemical weapons testing. Island access at this time may have resulted in considerable disturbance to some areas of the Brook Island fringing reef. At the present time there is an unmanned lighthouse on South Brook Island. North, Tween and Middle Islands of the Brook Group were gazetted National Parks in 1936, NP 390, 391 and 392, respectively. Little clearing of the natural vegetation of the Brook Islands or Goold Island has taken place.

2.4 *Summary:*

The Tully River catchment is predominantly granitic. A little less than one third of the catchment area is Quaternary alluvium. Physiographically, the catchment consists of three regions:- a plateau in the west, a series of roughly parallel ranges aligned with the structural trend, and the depositional landforms of the alluvial and coastal plains. The Tully River can be classified into five reaches:- a plateau reach, an upper and a lower gorge reach, and an upper and a lower alluvial reach. Although there is considerable morphological evidence of past stream channel instability, during the historical period the Tully River channel has been stable. Soils have largely developed on, or are derived from, granites or alluvium.

The climate is humid, tropical with a strongly seasonal rainfall averaging 4 200 $mm.a^{-1}$ at Tully, lower in the west and south of the catchment, and higher on the coastal ranges. The ten year recurrence interval daily rainfall at Tully is 480 mm. An important determinant of soil erosion rates is rainfall erosivity which is usually calculated from continuous pluviograph data. Long term pluviograph data is not available for the region demanding that another measure of rainfall erosivity be found if this important factor is to be included in sediment yield studies. It has been shown that quite good estimates of rainfall erosivity can be obtained using daily data raised to an exponent in the range 1.5 - 2.0. There is evidence of a strong, decreasing trend in rainfall erosivity at Tully since the late 1940s. The trend is regional for stations with annual rainfall > 2 000 mm, although it is most pronounced at Tully. Seasonal rainfall erosivity patterns are hysteretic, with the highest relative intensities in the December - January period. Winds in the study area are predominantly onshore throughout the year, with southeasterlies predominating in the March - July period and northeasterlies in September - December. On average, onshore wind energy is lowest during the wet season.

Mean annual runoff from the Tully catchment is about 2 200 mm, or 74 % of the catchment mean annual rainfall. Regional comparison shows the runoff coefficient to be high, and the inter-annual variation in stream flow to be low.

The vegetation of the uplands is predominantly mesophyll vine forest. Prior to European settlement and land clearing, much of the lowlands was complex mesophyll vine forest, with coastal and floodplain complexes of *Eucalyptus* and *Melaleuca* dominated open forest and woodland.

There is circumstantial evidence that lowland vegetation at the time of European settlement was strongly influenced by previous Aboriginal land management practices, particularly burning. Earliest agriculture took place in 1866, with small areas of sugar cane plantation on the Tully River banks from the 1880s. Banana growing was important in the first two decades of this century. The first significant land use intensification, for cane growing, occurred following construction of the Tully Mill in 1925. Large-scale land clearing for pasture occurred during the early-1960s, and there was a further cane land expansion in the late-1970s, associated with increasing areas under banana cultivation. Most of the land cleared for agriculture and pasture in the Tully catchment has low erodibility, largely because land clearing is almost entirely confined to the alluvial plains and little steepland has been cleared. In this respect, the Tully catchment differs from others in the region, such as the North and South Johnstone Rivers, where steep slopes are cultivated, but has a similar pattern of land utilisation to the Herbert River and Liverpool Creek catchments.

Significant changes in land management have taken place during the post-settlement period. Pre-harvest burning of the cane has been practiced since the 1940s, and mechanical harvesting and loading since the 1950s.

More recently, adoption of zero tillage and residue retention has probably led to a decrease in soil loss, perhaps by as much as an order of magnitude, on farms where it is implemented. However, Tully cane growers have the lowest rate of adoption of these techniques in the north Queensland wet tropics.

Although there are some uncertainties in the quality of fertiliser inputs data, it is clear that application rates and areas fertilised have increased significantly over the last forty years. The greatest increase is attributed to banana cultivation, and the proportion of fertiliser applied to pasture has declined markedly since the early 1970s.

Land use on the islands of Rockingham Bay is largely limited to resorts on leeward sand spits of the two larger islands, Dunk and Bedarra. Most of the islands, and most of the area of the islands, is essentially in its natural state, protected by National Park status since the 1930s.

CHAPTER THREE

WATER QUALITY IN THE TULLY RIVER CATCHMENT

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3.0 GENERAL INTRODUCTION:

In this chapter the rationale behind the choice of methods for investigating spatial and temporal variation in water quality, particularly suspended sediment concentrations, in the Tully River is discussed and the methods used are described. Fieldwork was undertaken in the periods November, 1987 to March, 1988 and during March - April, 1990. The meteorological and oceanographic conditions during these periods are described, and are relevant to the ensuing discussion in this chapter and in Chapters 4 and 5.

Contextual data outlining the relationships between turbidity and suspended sediment concentrations, and between conductivity and total dissolved solids, in Tully catchment streamwaters is described in Chapter 3.4, as is a brief discussion of atmospheric accession to the catchment and a simple rainfall-runoff model.

The remainder of this chapter discusses the characteristics of stream sediment and solute concentrations with particular emphasis on their relationship to catchment characteristics including land use. These characteristics are then used, in Chapter 4, to infer a time series of change in sediment yield in response to the land use changes outlined in Chapter 2.3 and changes in rainfall erosivity as outlined in Chapter 2.1.

Apart from establishing a sediment yield chronology for the catchment, in relation to changes in land use and climate, the relevance of this chapter to the study lies in establishing whether the Tully is typical or exceptional among humid tropical catchments, both regionally and globally. To this end, the sediment load and the relative contributions of chemical and mechanical denudation processes are estimated and contrasted with relevant examples.

3.1 MEASUREMENT OF SOIL EROSION, SEDIMENT YIELD AND STREAM SEDIMENT AND SOLUTE CONCENTRATIONS:

3.1.1 Sediment yield from the Tully River:

In some regions the choice of methods for identifying and quantifying sediment sources is limited by the highly episodic manner in which erosion events occur. For example, Hereford (1987) found that sediment delivery occurred only 21 times in 38 years in a 2.8 km^{-2} catchment in southern Utah. In the case of the wet tropics, however, sediment delivery is likely to occur during numerous runoff events in a single wet season. As a result of the frequency of sediment yielding events and the relatively low inter-annual discharge variability of catchments in the wet tropics, many of the sampling problems experienced by workers in more variable climates are minimised. Nevertheless, decisions must be made as to the most practical method of water quality sampling.

Studies of reservoir and lake sedimentation have been used to investigate relationships between land use change and catchment sediment yield (eg. Oldfield *et al.*, 1978; Dearing *et al.*, 1982) especially at timescales relevant to catchment management (Wasson and Clark, 1985; Clark and Wasson, 1986). Reservoir sedimentation studies have been used as the standard against which other methods of calculating sediment yield have been evaluated (Bogardi *et al.*, 1986). However, application of this approach in the Tully catchment is limited by a number of factors, the most important of which is that land use change has only occurred downstream of the only large dam (Koombooloomba) in the catchment. Characteristics of the Koombooloomba dam catchment are quite different from those of the remainder of the study area.

Sediment yield measurement using stream suspended sediment concentrations has three basic components:-

i. Field sampling: Sampling methods must take account of vertical and lateral variations within the stream (discussed in 3.2.1). Given that streams generally transport a large percentage of their load during a small percentage of time, temporal variation is also important in sampling. As a result, event based sampling is now more commonly used (Olive and Walker, 1982) as it minimises the underestimation of sediment yield resulting from infrequent, regular sampling (Dickinson, 1981) by characterising sediment transport when it is most effective.

An alternative approach to manual removal of a water sample is automated sample removal using, for example, Manning samplers, or direct monitoring of sediment concentrations using continuous turbidity measurement, nuclear and ultrasonic sediment concentration instruments, and continuous centrifugation. These methods have been successfully used to measure stream suspended sediment concentrations and have the advantage of frequent determinations during low frequency, high magnitude events. Each has the drawback of relatively high capital cost for an installation at a single site, and prohibitive cost in water quality monitoring at a large number of sites. Manning samplers are limited by a finite number of samples. Nuclear methods are ineffective at low sediment concentrations (< c. 1 000 $mg.l^{-1}$; Tazioli, 1981) and ultrasonic methods at high concentrations (Dhillon *et al.*, 1981). A further disadvantage is the possibility of malfunction during a significant sediment transport period.

Turbidity can be measured either *in situ* or on samples removed from the stream. Strictly speaking, a distinction must be drawn between the measurement of turbidity as the measurement of attenuation along the light path, and the measurement of nephelometric turbidity, in which light scattering is determined. Reliable and economical commercial instruments are available to measure the optical properties of water. They are most suitable for waters with sediment concentrations < 1 000 mg.l^{-1}, often the case in Australian coastal streams, although Wolanski *et al.* (1988) obtained a strong, linear relationship between turbidity and SSC for South Alligator River waters with SSC > 5 000 mg.l^{-1} using an Analite nephelometer.

Empirical relationships between suspended sediment concentration and turbidity have been derived with a very close correlation between these variables (e.g. Kunkle and Comer, 1971; Finlayson, 1985), but other studies have found a relatively poor relationship (e.g. Lammerts van Bueren, 1984; Anderson and Potts, 1987). The relationship may vary between streams in a catchment (Lammerts van Bueren, 1984), between and during events (Gippel, 1989; 153 - 171) and possibly between seasons (Gippel, 1989; 25), and may take a linear, log - linear or polynomial form.

The relationship between SSC and turbidity is influenced by the size, shape and mineralogy of the particles and the concentration and composition of organics. Gippel (1988, 1989) reviewed recent analyses of these relationships and investigated them in detail for streamwaters in a small forested catchment at Eden, southeastern Australia. Specific turbidity (attenuation corrected for particle concentration) is low for very small particles, reaches a maximum for particles of about 0.5 to 1.0 µm and then declines such that particles $\geq$ 100 µm contribute little to beam attenuation (Campbell and Spinrad, 1987). Gippel (1989; 30) suggests that differences in specific gravity and diffraction index could influence scattering efficiency, but a more important difference between minerals is likely to be particle shape as quartz (Pak *et al.*, 1970) and smectite (McCarthy *et al.*, 1974) scattering are about half as efficient as kaolinite.

The ubiquitous presence of dissolved organic substances in soil, lake, stream and marine waters (Aiken *et al.*, 1985) colours the water which influences turbidity. The spectral characteristics of this organic discolouration, referred to as gilvin (Kirk, 1976), are such that they are of little importance at wavelengths > 600 nm (Davies-Colley and Vant, 1987).

Turbidity meters may also be quite sensitive to sample temperature. Gippel (1989; 121) recorded fluctuations of $\pm$ 10 % in response to diurnal temperature variations over a range of 4^{o}C. (Partech 7000 3RP MkII with S100 sensor)

ii. Laboratory determination of suspended sediment concentrations: Measurement of the particulate concentration is necessary either to determine the concentration *per se* or to calibrate other measures. The standard, gravimetric method of filtration using pre-dried, pre-weighed 0.45 µm filter papers is accepted as having a high level of accuracy (Gippel, 1989;1). However, in many streams a significant proportion of suspended sediment passes through a 0.45 μm filter paper. In Geebung Creek, for example, between 0 and 63.5 % ($\bar{x}$ = 12.7 %) of 'total' suspended sediment (0.22 μm filter) was not trapped on a 0.45 μm filter (Gippel, 1989; 135). About 35 % and 22 % of suspended sediment in Jackmoor Brook and the River Dart, respectively, was ≤ 0.05 μm (Peart and Walling, 1982).

iii. Sediment load estimation: The most widely used method of sediment load estimation from concentration and discharge data is the rating curve method, limitations of which have been reviewed by Walling (1977a, 1977b, 1978) and Walling and Webb (1981). These studies have drawn attention to errors in load estimation associated with seasonal effects and hysteresis during events or through a series of events. These errors can be greatly reduced by use of individual rating curves which take account of these factors. Different methods of calculating the stream load from the flow duration curve can also lead to widely varying results. In general errors will be lower for larger catchments, and much lower for estimates of annual load than for monthly load. An additional systematic error is induced when a log -transformed least-squares regression model is used for load estimation because the arithmetic mean of two log-transformed values, when anti-logged (back-transformed), is less than the arithmetic mean of the two untransformed values (Ferguson, 1986a,b).

Although the sources of error in the estimation of suspended sediment loads are also generally applicable to solute loads, as a result of the much lower variability of solute concentrations the associated errors are proportionally lower.

The traditional rating curve approach remains a viable method for evaluating stream water quality, provided its limitations and particular characteristics are taken into consideration when attempting to calculate absolute values or compare data sets.

3.1.2 Spatial variation in sediment yield in the Tully catchment:

A total of 52 sites were selected for monitoring in the Tully catchment. The large number of samples required over the discharge range means that development of rating curves is an impractical method of estimating spatial patterns of catchment sediment yield in this study. Furthermore, the high probability of access to sampling sites being prevented by flood waters during significant events means that sampling will be biased to relatively low flows.

Manning samplers, continuous turbidity measurement and continuous centrifugation are prohibitively costly for water quality monitoring at a large number of sites.

A common approach to within-catchment erosion studies is the erosion plot method, used in the generation of the "Universal Soil Loss Equation" (Wischmeier, 1976; Wischmeier and Smith, 1978). However, erosion plots must be maintained over years, and in some cases decades, if useful data are to be obtained.

Hadley (1980) pointed out the potential of the > 2 million small reservoirs in the United States for investigation of catchment processes. In many areas of Australia large numbers of small dams are constructed on rural properties. For example, in one small catchment on the Southern Tablelands of New South Wales the density of farm dams increased from 0.24 $.km^{-2}$ in 1959 to 4.3 $.km^{-2}$ in 1972 and to 15.9 $.km^{-2}$ in 1985 (Srikanthan and Neil, 1989). Sedimentation surveys of these dams allow measurement of sediment yields of relatively small subcatchments over the life of the dam. Analysis of the trapped sediments may be used to reconstruct sediment yield histories of small catchments (Hereford, 1986, 1987), to investigate relationships between land use and sediment yield in small catchments (Neil and Fogarty, 1991), and the relationships between sediment yield and characteristics of the dam catchments may be used to map estimates of sediment yield over large areas of similar terrain at relatively low cost (Neil and Mazari, 1993). This approach is relatively simple to apply, requires no specialist equipment and is economical to implement. However, although topographic maps (1:25 000; 1:50 000) show the presence of many small dams in the Tully catchment, largely on the floodplain, on-site inspection shows that these are generally little more than excavated 'tanks' with no definable catchment area. As such they are quite unsuitable for sediment yield determination.

Radionuclide and mineral magnetic sediment tracing techniques have been shown to be useful sediment sourcing tools, but require specialist analytical equipment. The mineral magnetic method can be applied to streamwater samples of sediments in suspension, although filtration of very large volumes of water is required (Walling *et al.*, 1979).

Spot sampling as instantaneous, random sample withdrawals has the potential to indicate relative, rather than absolute, spatial variation in suspended sediment and solute loads within a catchment. For example, Walling and Webb (1975) investigated spatial variation in water quality in the River Exe by collecting water samples from over 500 sites in that 1 462 km^2 catchment with an altitude range of 500 m and mean annual rainfall from 850 to 1700 mm. The sites sampled had catchments with a variety of lithologies and land uses. Conductivity was measured on each sample and a calibration relationship with total dissolved solids was established.

Sampling was carried out within a 12 day period at a time of low streamflow. Significant variations in conductivity with lithology, and with land use within the lithological classes was evident. Yu and Neil (1993b, c) examined spatial variability in salinity of stream waters in the Williams River, southwest Western Australia using this approach, and found that spatial variation in rainfall, topography and geomorphology were important determining factors.

The spot sampling approach is likely to be more reliable for solute loads, which have lower variability than streamflow, than for suspended loads which are usually much more variable than streamflow. It seems likely that spot sampled data can be interpreted with greater confidence if results are consistent over a range of streamflow conditions, streamflow conditions are reasonably consistent between the sites sampled, and that results are consistent within terrain and land use classes. Given these caveats, spot sampling was selected as a practical and economical method of investigating spatial variation of suspended and solute loads in the Tully River catchment.

3.2 *METHODS:*

3.2.1 *Water sampling:*

A major problem in sampling spatial variation of water quality in wet tropical catchments is accessibility of a sufficiently diverse range of sites. The Tully catchment is well served in this respect with cross river bridges at 17.5 km AMTD and 72 km AMTD. A sealed road provides access along the north bank of the river and an unsealed road (generally requiring a four-wheel drive vehicle during the wet season) on the south bank. These roads cross numerous tributary streams (Fig. 3.2.1), the catchments of which have a wide variety of physiographic and land-use attributes. Three detours from these major access roads provide further suitable sampling points. In addition, Banyan Ck., one of the four major subcatchments of the Tully River and the one with the most intensive agricultural and infrastructural development, also has good access to sampling points with a wide range of catchment attributes. Sites were chosen on the basis of their variability of catchment attributes, and their ease and safety of access. All samples were obtained by dip sampling at the deepest point, from within 10 cm of the water surface, irrespective of stage or velocity, from road bridges.

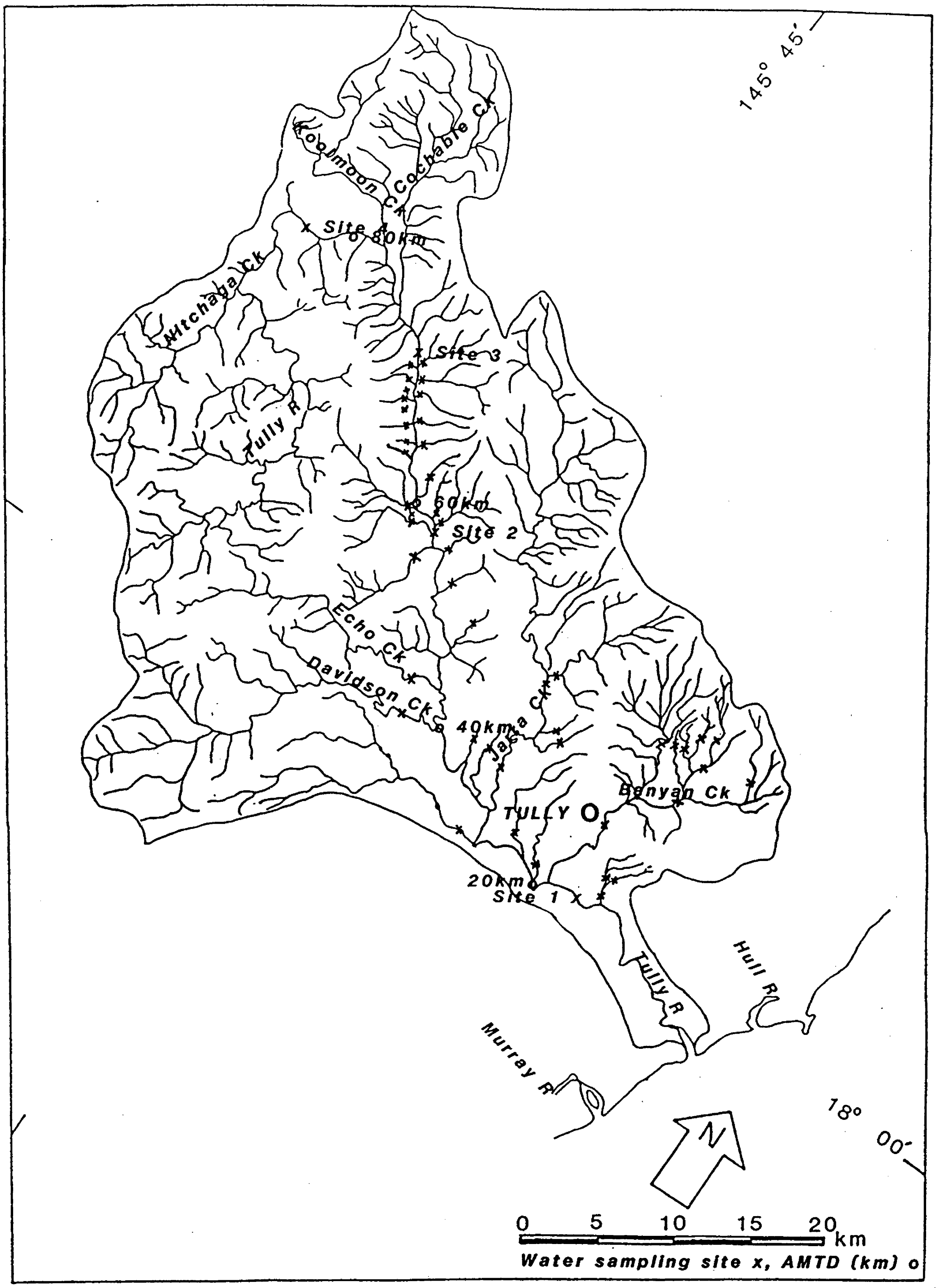


Fig. 3.2.1
Location of stream sampling sites in the Tully River catchment.

Turbulent diffusion of solutes leads to a symmetrical and eventually uniform cross-channel distribution (Sayre and Chang, 1968) and Richards (1982: 91-92) concludes that solutes from diffuse sources can be confidently sampled by mid-channel point withdrawals. Cross-channel variation of <5% (Johnson, 1971) with concentration gradients <0.05 ppm.m^{-1} (Glover and Johnson, 1974) have been described for turbulent streams. This uniformity of distribution can be achieved over mixing lengths <250 m in fast flowing streams (Day, 1975). Richards (1982: 92) also points out that in deep, sluggish reaches or wide, shallow streams lateral sample integration may be more appropriate. In general, the streams sampled in the Tully catchment tend to be narrow and fast flowing and therefore single point dip sampling is expected to yield reliable results.

Sampling of suspended particulates is considerably more complex as lateral and vertical gradients can occur. Vertical concentration gradients increase closer to the bed and lateral gradients reflect lateral velocity gradients. However, as demonstrated by Colby (1963) on the Mississippi River and by Belperio (1979) on the Burdekin River, the distribution of very fine particles (eg. < 0.0625 mm) resembles that of solutes while the coarse load is less uniformly distributed. Although most streams exhibit lateral and vertical gradients, the variability is often sufficiently small that a point sample is representative of the section (e.g. Allen and Peterson, 1981). Because this study is largely concerned with clay-size detrital inclusions in coral skeletons, it is appropriate to determine the SSC and accurate determination of the coarse load may be disregarded. A preliminary check on the validity of point sampling was made by measuring the lateral variation in two streams, one sand bed and the other cobble bed. The coefficient of cross-channel variation was low, 6.2 % and 3.6 % respectively. The lateral variation was only 1.5 times the temporal variation, recorded over a 30 second period in both cases. Consequently, the use of dip sampling from the top of the depth profile is appropriate for this study, but does mean that total SSC will be underestimated.

A further complexity in the characteristics of suspended sediment particle size is changing size distributions with changing land management practices. For example, Prove (1991) demonstrated that the shift from conventional tillage to zero tillage and green cane harvesting resulted in decreased sediment concentration, and increased exchange capacity and specific surface area. It follows that particle size distribution shifted to smaller sizes.

Water sampling (Table 3.2.1) was structured to provide five overlapping data sets:

(i) A circuit of the catchment, largely between the two bridges, provided data from a relatively large number of sites of diverse catchment characteristics, with infrequent sampling. Samples were obtained at 46 sites (Fig 3.2.1) on fifteen occasions during the 1988 field trip. Stream stage was recorded from a fixed datum on each bridge from which samples were collected. No sampling was carried out on this circuit during the 1990 field trip as, for most of the time, the south bank roads were impassable due to flooding. A circuit was usually completed within 7 hours.

(ii) Much more frequent sampling of streams in the Banyan Creek catchment was carried out. Subcatchments of Banyan Creek were chosen for a range of cultivation from 0 to 50% of their area. Nine sites (Fig 3.2.2) were sampled 58 times in 1987-88 and 25 times in 1990. Stage height was recorded at each sampling during the 1988 and 1990 field trips at eight of these sites. These sites are included in data set (i). Additional samples were obtained from a site, immediately upstream of which was a major construction site (43 samples, 1988) and from the small catchment in which most of Tully town lies (43 samples, 1988).

(iii) Long profiles of Tully river water quality were obtained using 3 sites at 17.5 km AMTD (Site 1), 57 km AMTD (Site 2) and 72 km AMTD (Site 3). Samples were obtained simultaneously (within driving time) at these sites. On a number of occasions, additional samples were collected at 84 km AMTD (Site 4). Stage at the time of sampling was recorded at two of these sites (1 and 3).

(iv) Water samples were obtained from the Tully River at the site of the Euramo road bridge (Site 1; 17.5 km AMTD) on 103 occasions in 1987-88 and 54 in 1990. Although this is the site of the QWRC gauging station (113006A), river stage was always recorded in case the automatic recorder failed. This site is about 2.5 km above the tidal limit as defined by QWRC. Sampling was generally on a daily basis, but more frequently during periods of hydrological activity. In addition, 15 samples in 1987-88 and 14 in 1990 were obtained from the Murray River at the highway bridge (c. 27 km AMTD).

(v) Water samples were taken opportunistically from unsealed and sealed road runoff, banana farm irrigation runoff, and from streams upstream and downstream of confluences with unsealed road runoff.

	Sampling period					
	1987-1988			1990		
	No. of samples		No. of sites	No. of samples		No. of sites
Sample type						
Sampling circuits:						
Tully catchment	15	x	46	-		-
Banyan catchment	58	x	9	25	x	9
Long profiles:						
Tully River	15		3			
	(7 incl. Site #4)					
Stream samples:						
Tully River	103		1	54		1
Murray River	15		1	14		1
Banyan (urban)	43		1			
Banyan (construction)	43		1			
Opportunistic sampling:						
Unsealed road runoff	21					
Sealed road runoff	8					
Banana irrigation runoff	5					

Table 3.2.1
Summaries of stream water sampling series.

Daily rainfall was sampled at both Tully and Cardstone during the period November 1, 1987 to March 10, 1988. The samples were obtained from Bureau of Meteorology rain gauging stations (032042 and 031115) on 63 and 45 occasions, respectively. The differing number of samples reflects the number of rain days at these sites during the sampling period. Conductivity of these samples indicates the ionic precipitation at two distances from the coast. Receptacles were not cleaned between samplings, so results are the total of wet and dry precipitation.

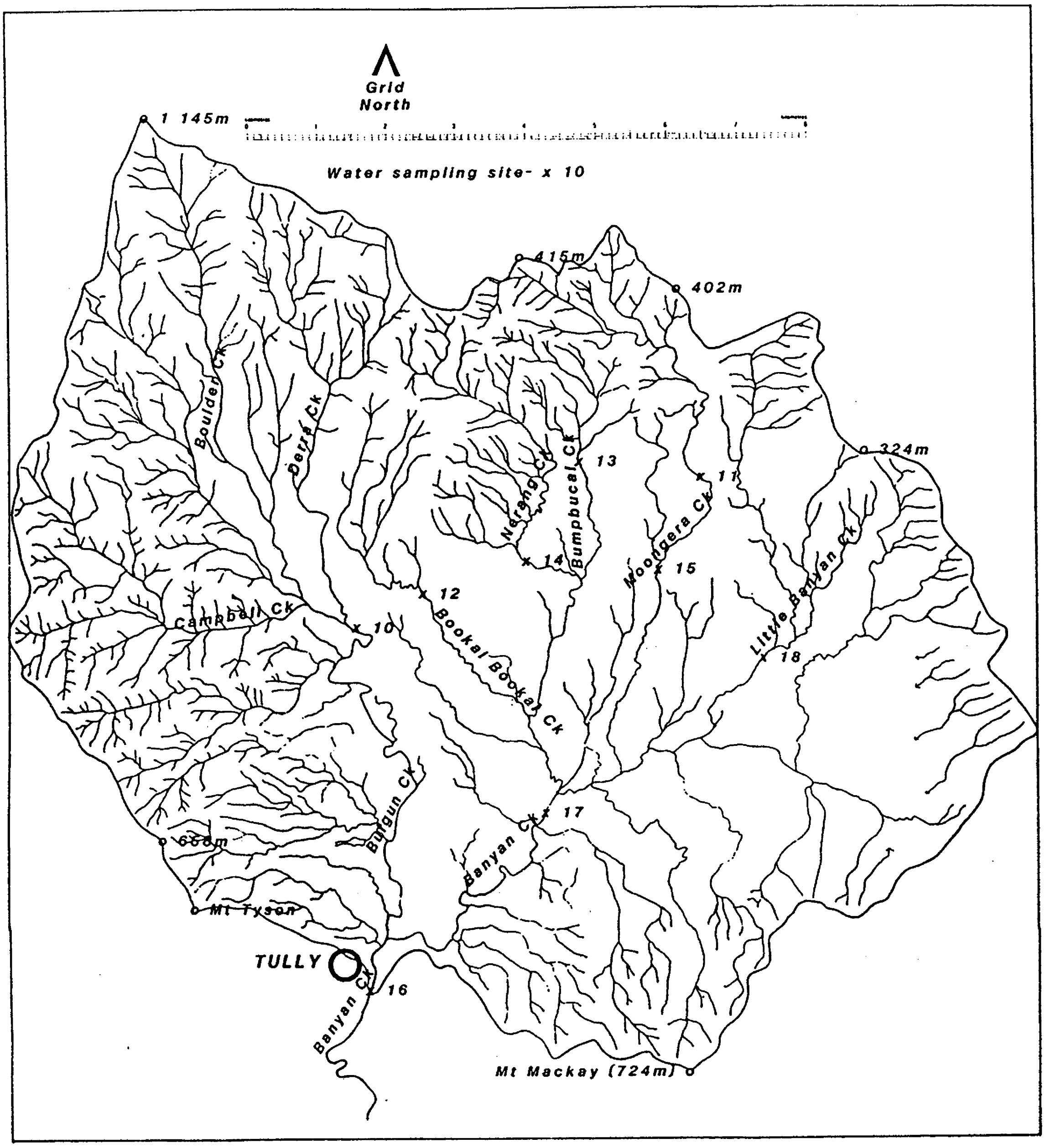


Fig. 3.2.2
Location of stream sampling sites in the Banyan Creek catchment.

3.2.2 Survey and streamflow:

The physiographic characteristics of the Tully catchment and subcatchments were determined by the following methods. Catchment areas were measured from the 1:50 000 topographic sheets (contour interval 20m) using a Planex digital planimeter, which was also used to measure the area of each catchment in the surficial geology class mapped by de Keyser (1964; Innisfail 1:250 000 sheet) and de Keyser *et al.* (1972; Ingham 1:250 000 sheet). The area of each subcatchment in the Banyan Creek basin with transported soils (colluvial and alluvial) was measured from the 1:50 000 soil maps (Murtha, 1986). Land use was determined from the 1:50 000 and 1:25 000 topographic sheets (based on 1978 aerial photography) with reference to air photos and ground truthing and verification during field work. Catchment roading, unsealed roads only, was also determined from the 1:50 000 sheets with ground verification.

Stage measurements at selected sampling sites were converted to discharge using the Chezy-Manning equation (Linsley, Kohler and Paulhus, 1975):

$$Q = n^{-1}.D^{.66}.s^{.5}.A \qquad \text{[Eqn. 3.2.1]}$$

where: n = roughness coefficient
D = hydraulic radius
s = slope
A = cross-section area

Channel cross-sections were surveyed at low stage. Current monitoring over the range of stage heights observed was not possible for the single surveyor. Values of n, from the tabulation of Linsley *et al.*, (1975: 446), D and A were determined for stages at $\leq$ 0.50 m increments for each section and a rating curve constructed. For the sake of convenience, the conversion of observed stage heights to discharges was by fitting a 4th order polynomial to the rating curve for stage <2m, and also for all stages up to the maximum observed, and applying the equations derived to observations <2m and >2m respectively. This approach induced no marked discontinuities in the stage/discharge relationship over the range of streamflows observed. Although the instability of high order polynomials has long been recognised (Forsythe, Malcolm and Moler, 1977: 69), in this application the equations are used only for interpolation, and then only on monotonically increasing data sets.

The Chezy-Manning method is subject to substantial uncertainty, especially in relation to the estimation of 'n' (Linsley *et al.*,1975; 128), and also in the measurement of slope and estimation of discharge for overbank flows. The latter problem also applies to gauging at the Euramo gauging station on the Tully River. Discharge at the Tully River for periods when the automatic recorder was not working was calculated by correlating stage measurements made at the bridge at times of water sampling to stages logged while the recorder was working. The QWRC rating curve for the station was then used to calculate Q for each observation.

Stream channel cross-sections were surveyed at most of the sites from which water samples were collected. Most surveys were done during November and December, 1987 at the end of the dry season. Bridge rails and road levels were used as local benchmarks, and levels were measured with a surveyors staff for channels within 5m below the datum, and with a leadline for depths below 5m. As all surveys were undertaken at baseflow little error is induced by use of the leadline. Channel characteristics were noted in order to estimate the appropriate values for the Manning roughness coefficient.

3.2.3 Analytical methods:

3.2.3.1 Turbidity and conductivity:

Turbidity and conductivity were measured on all samples on the day of collection, generally within eight hours of commencement and one hour after completion of a sampling circuit. In most cases, determinations were made within three hours of sampling. Delay in turbidity determination after sampling has been shown to be important in stream waters in which the particulate load is dispersed. In waters dominated by Na^+ (Cornish and Binns, 1987), Gippel (1989) suggests that, at least under turbulent stormflow conditions, suspended particulates will be dispersed. A progressive decline in turbidity in relation to storage time was observed by Gippel (1989; 128) in samples which were reshaken before each determination. As this decline amounted to about 4 % after 24 hours, errors in the present study should be less than about 2 %. Instruments were switched on 30 minutes before measurements were made to ensure that they stabilized.

Turbidity was measured using an Analite Model 155 digital nephelometer (BWD Precision Instruments, Australia) with a measuring range of 0.1 to 2000 NTU. The instrument was zeroed using deionised water (Queensland Ethicals, Australia) prior to each set of measurements, rinsed in deionised water between determinations and checked for drift at the completion of analyses. Drift was generally < 0.5 NTU over the measuring period, and was linear. The necessary corrections for measured drift were then made.

The Analite nephelometer operates at a wavelength of 900 nm so it is quite insensitive to gilvin concentration. It has a claimed accuracy of $\pm$ 2 % $\pm$

1 digit and this error applies within $\pm$ 5 ^{o}C of the calibration temperature (23 $\pm$ 3 ^{o}C), a range within which most of the samples lie. Temperature fluctuations should not be a significant source of error. The light source is modulated at 50 Hz, so that turbidity determinations should be independent of ambient light (Wolanski *et al.*, 1988).

Conductivity was measured with a Schotte-Gerate CG857 digital conductivity meter (Schotte-Gerate GMBH, FRG), with a measuring range of 0.1 uS.cm^{-1} to 19.99 mS.cm^{-1} and no temperature compensation, during 1987-1988. For the 1990 field season a TPS Model LC81 digital conductivity meter with automatic temperature compensation (TPS Pty Ltd, Australia) was used. No significant drift was observed in either of these instruments after the stabilisation period. Temperature corrections (1987-1988) were made using the formula:

$$LR = LT - 0.02\,(T-R)\,LT \qquad \text{[Eqn. 3.2.2]}$$

where LR = conductivity at reference temperature
LT = conductivity at sampled temperature
R = reference temperature
T = sample temperature (Gardiner and Dackombe, 1983:154)

The reference temperature used is 25^{o} C and all sample temperatures were within 5 ^{o}C of this. pH determinations were made on a number of samples and indicate that no correction of conductivity for pH (Finlayson, 1979) was required. These analyses were done with a Radiometer ION83 digital pH meter (Radiometer A/S, Denmark). Selected samples were refrigerated and retained for further analyses.

Calibration curves defining the relationship between turbidity and suspended sediment concentration and between conductivity and total dissolved solids were derived. Water samples (500ml) were passed through predried, preweighed 0.45 µm pore size cellulose nitrate filters at low vacuum. The filter papers were oven dried (100^{o} C) and reweighed (to 0.0001g) to determine SSC. Organic and inorganic particulates are not discriminated in this analysis. After filtration aliquots were placed in preweighed beakers, the filtrate evaporated and the beakers reweighed to determine TDS.

3.2.3.2 *Elemental analyses:*

Determination of solute concentrations (Total N, Si, Cl, SO_4, Mg, Ca, K, and Na) was carried out on selected water samples. Treatment of these samples was by resuspension of sediment using the Braun Labsonic 2000 (1.9 cm) ultrasonic probe for 5 minutes. Walker and Hutka (1973) found that ultrasonic dispersal was a suitable method for disaggregation of soil samples when the integrity of coarse particles was required, a finding supported by the results of other workers investigating particle size distribution and dispersal in soil materials (eg. Heller *et al.*, 1984; Moen and Richardson, 1984). The ultrasonic method of resuspension of sediments in stored stream water samples is recommended by Gippel (1989) who compared vigorous hand shaking, sonic bath and sonic probe methods and found that the ultrasonic probe resulted in the highest turbidity per unit suspended solids and laboratory turbidity, after storage and resuspension, was well correlated (1:1) with field turbidity results.

After ultrasonic resuspension to restore particle size distributions as closely as possible to their natural state, all samples were filtered through Sartorius 0.45 µm pore size (49 mm diameter) cellulose-nitrate filters. Filter papers (with residue) were air dried and retained for further analysis and the solute concentrations in the filtrate were determined. PO_4-P, Si, Cl and SO_4 were determined using the Technicon Auto Analyser MkII, and Mg, Ca, K, Na, and Sr with a Varian AAS MkVI. Total N was determined using the Kjeldahl method (Bremner and Mulvaney, 1982).

3.2.3.4 X-ray diffraction:

X-ray diffraction analysis was carried out on the residual sediments retained on 0.45 µm cellulose nitrate filter papers. For these analyses a section of filter paper was attached to the glass slide using double-sided adhesive tape. Blanks of clean filter paper were tested and found to give no specific X-ray peaks. As a result of the changed solid angle due to the thickness of the filter paper and adhesive tape, the d-spacings of the emission spectra are reduced by about 0.8 %.

3.2.3.5 Particle size:

Particle size distributions (nine samples only) were determined using the Horiba CAPA-300 instrument in "multi-mode" (gravitional and centrifugal). Filter paper (0.45 µm) residues were resuspended in Isoton II using an ultrasound bath. The centrifugal sedimentation method employed by the CAPA-300 is described by Gippel (1988) who also compares the method and results from analyses on the CAPA-300 with those from the Coulter Counter. The CAPA-300 appears to underestimate the < 4 µm fraction although there was no significant difference between the two instruments for the < 2 µm fraction. The Coulter Counter truncates the distribution at 0.5 µm, a limitation which does not occur with the CAPA-300.

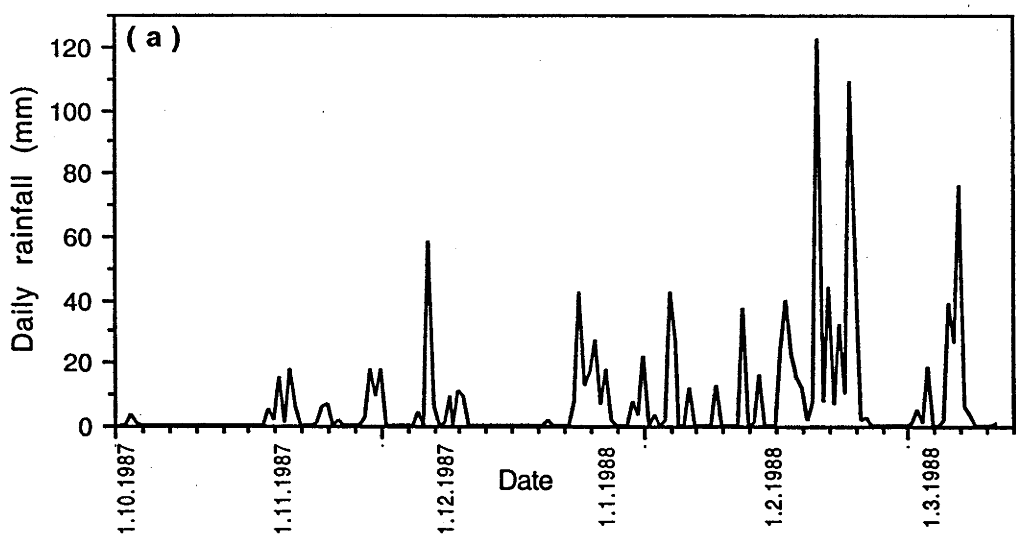
3.2.4 Statistical methods:

Throughout this and the following chapters, correlation and regression analysis are frequently used to test associations and predictive relationships between variables. The coefficient of determination of the correlation is expressed as r^2, and the coefficient of determination of the regression is expressed as R^2. The statement that a relationship is significant implies that it is significant with an error probability ≤ 0.05 using a t-test, and that variances were not significantly different from equality using the F-test.

3.3 METEOROLOGICAL CONDITIONS DURING SAMPLING PERIODS:

3.3.1 1987 - 1988 Sampling period:

Sampling of stream waters in the Tully River catchment took place between 31.10.1987 and 15.3.1988. Rainfall during this period at Tully and at Cardstone is shown in Fig. 3.3.1. During this period rainfall was generally < 40 mm.dy-1 at Tully and < 20 mm.dy-1 at Cardstone. Rainfall at these two stations is positively correlated (r^2 = 0.42) during the sampling period. In February and early March, three rainfall events occurred which generated a significant rise in the Tully River (Chapter 3.5) with daily rainfall totals of 122, 109 and 76 mm at Tully.



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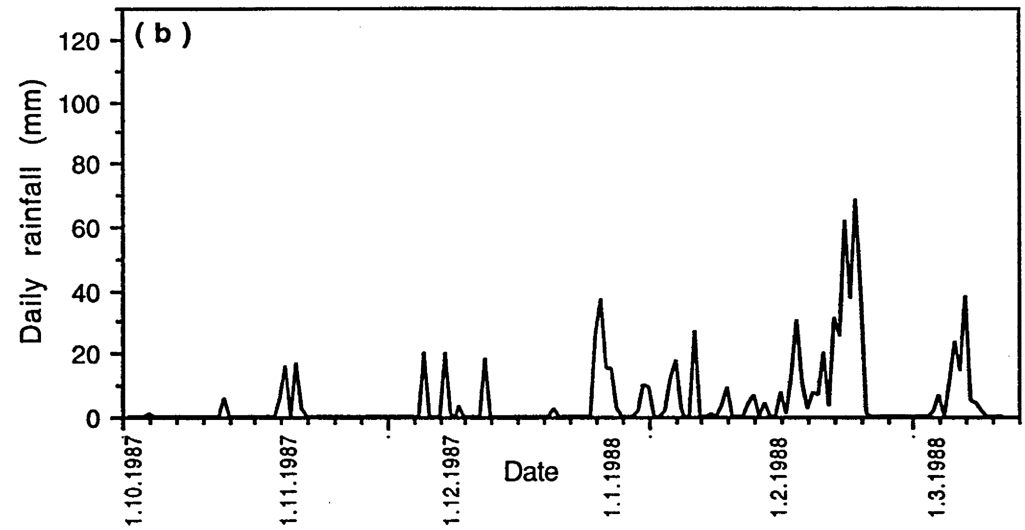


Fig. 3.3.1
Rainfall at Tully (a) and at Cardstone (b) during the 1987 - 1988 sampling period (Aust. Bur. Met. data).

Onshore wind speeds during the sampling period display a distinctly cyclical pattern (Fig. 3.3.2), with maxima in the cycle in the range 20 - 30 knots. No strong relationship between the temporal pattern of rainfall and the wind cycles is evident.

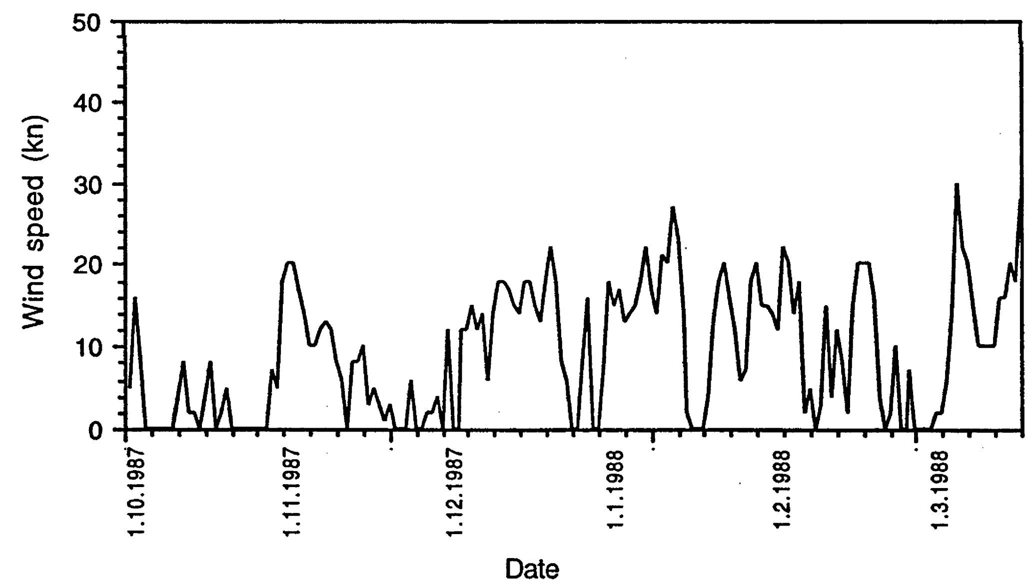


Fig. 3.3.2
Onshore (NE - SE) wind speeds (09.00) at Fitzroy Island (Stn. 31084) during the 1987 - 88 sampling period (Aust. Bur. Met. data).

<u>*3.3.2 1990 Sampling period:*</u>

Sampling of stream waters in the Tully River catchment and in Rockingham Bay was carried out during the period 19.3.1990 to 12.4.1990. During the early part of this period, meteorological conditions were dominated by the passage of tropical cyclone *Ivor* and, subsequently, by the depression into which it degenerated. A general description of the track and characteristics of *Ivor* is given by Ready and Woodcock (1992) and van Woesik *et al.* (1991) and Done *et al.* (1991) provide reviews of the impact of *Ivor* on reefs in its path, about 400 km north of Rockingham Bay. The latter part of the 1990 sampling period is influenced by the passage of high pressure systems across the southern part of Australia.

Rainfall at Tully commenced on 18.3.1990 as *Ivor* approached the coast in the vicinity of Cooktown (Fig. 3.3.3). Heavy rain (165 mm) fell at Tully on 20.3.1990 as the cyclone crossed the coast and again on March 23 and 24 as the depression moved southward toward Tully. Rainfall at Cardstone was quite similar to that at Tully during most of this period, with the notable exception that, on 24.3.1990 (the day of heaviest rainfall), that at Tully (349 mm) was more than twice the rainfall at Cardstone (141 mm). By comparison, the highest one-day rainfall recorded at Tully in the period 1925 to 1990 was 606 mm (11.3.1927). The total rainfall due to cyclone *Ivor* and the ensuing rain depression over 7 days was 770 mm at Tully, and 527 mm at Cardstone. During the month of March, 1990 a total of 1 260 mm of rain fell at Tully. Of 804 months of record, this ranks 31st. The data set includes 16 months when $\geq$ 1 500 mm of rain fell, the greatest being 2 003 mm in January, 1981.

The pattern of sediment plume movement in response to this rainfall and resulting runoff is discussed in Chapter 5.

Onshore wind speeds at Fitzroy Island (09.00) reached a maximum of 48 kn during the initial passage of cyclone *"Ivor"* across the coast near Cooktown (Fig. 3.3.4). By the time peak rainfalls from the subsequent depression occurred, onshore winds had fallen to the 0 - 15 kn range, but increased again in the last few days of March. During the first two weeks of April onshore winds were consistently in the range 10 - 20 kn.

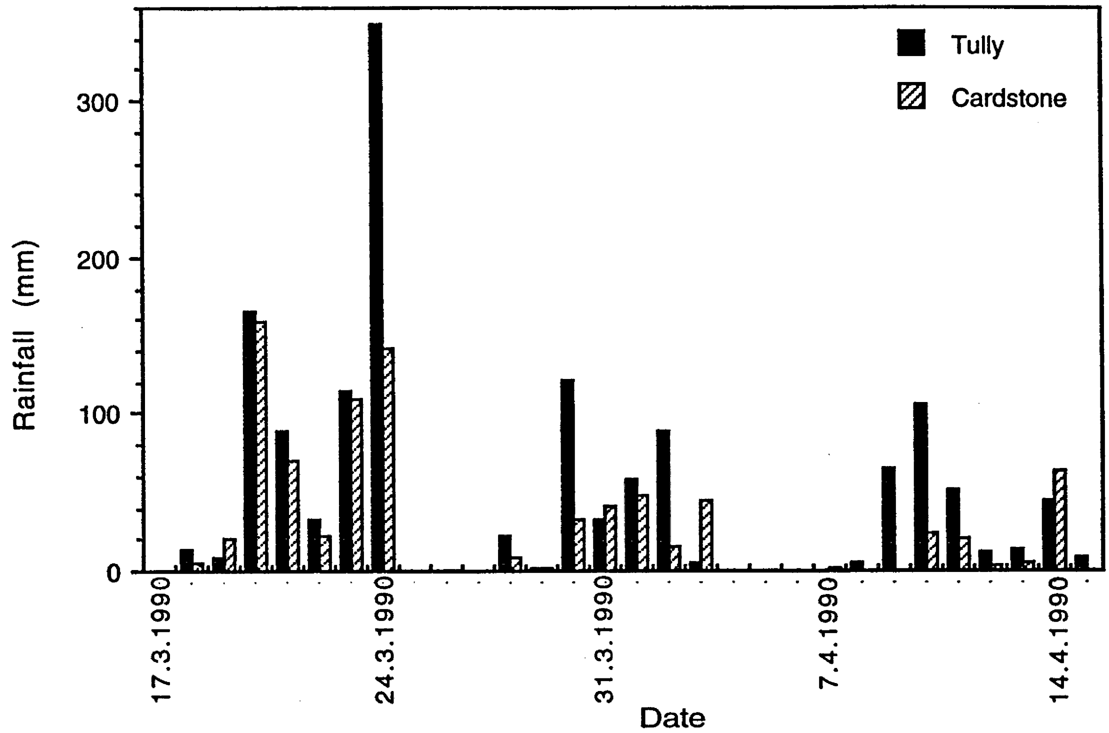


Fig. 3.3.3
Rainfall at Tully and at Cardstone during the 1990 sampling period (Aust. Bur. Met. data).

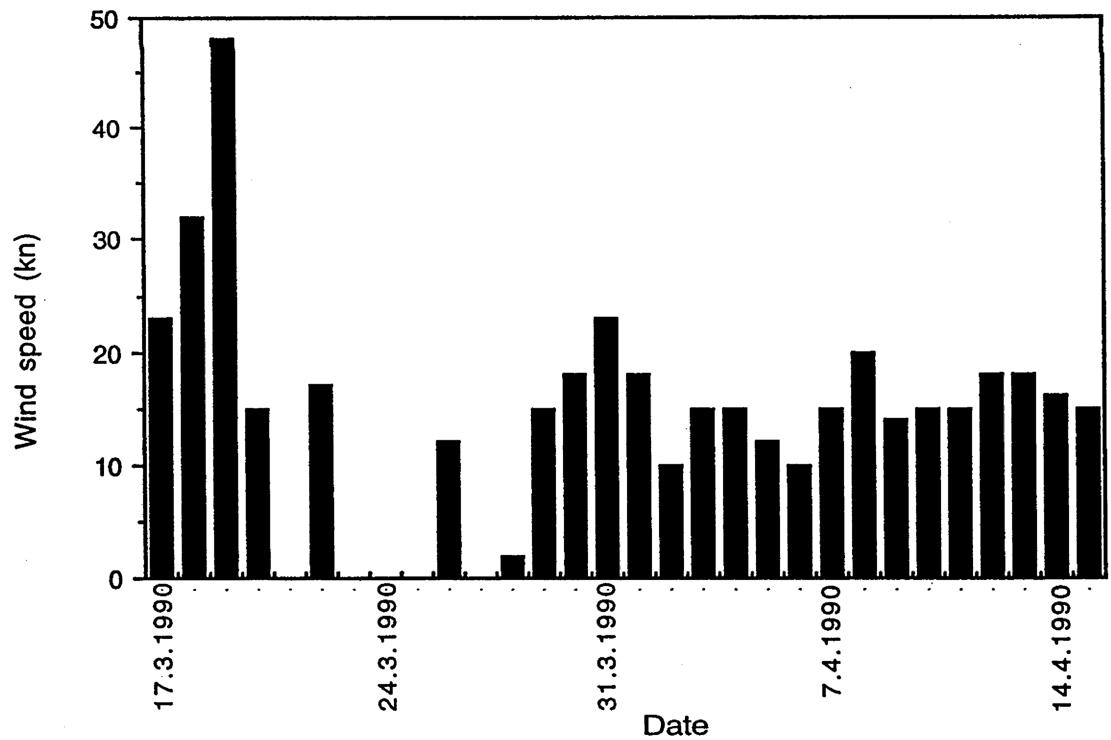


Fig. 3.3.4
Onshore (NE - SE) wind speeds (09.00) at Fitzroy Island (Stn. 31084) during the 1990 sampling period (Aust. Bur. Met. data).

3.4 *CONTEXTUAL DATA:*

3.4.1 Calibration of turbidity with suspended sediment concentrations:

Within the range of concentrations found in most Tully basin streams there is a strong correlation between turbidity and SSC (Fig. 3.4.1). The regression equation fitting Fig. 3.4.1 (a) is:

SSC = 1.2457 + 1.063.Turbidity + 0.0059.Turbidity^2 (n = 36; R^2 = 0.96) [Eqn. 3.4.1]

Although there is only one data point from high sediment concentrations to support it (Fig. 3.4.1 (b)), the following relationship is adopted for the few samples of NTU > 200:

SSC = 1.689.Turbidity + 0.00068.Turbidity ^{2} - 8.396 (n = 37) [Eqn. 3.4.2]

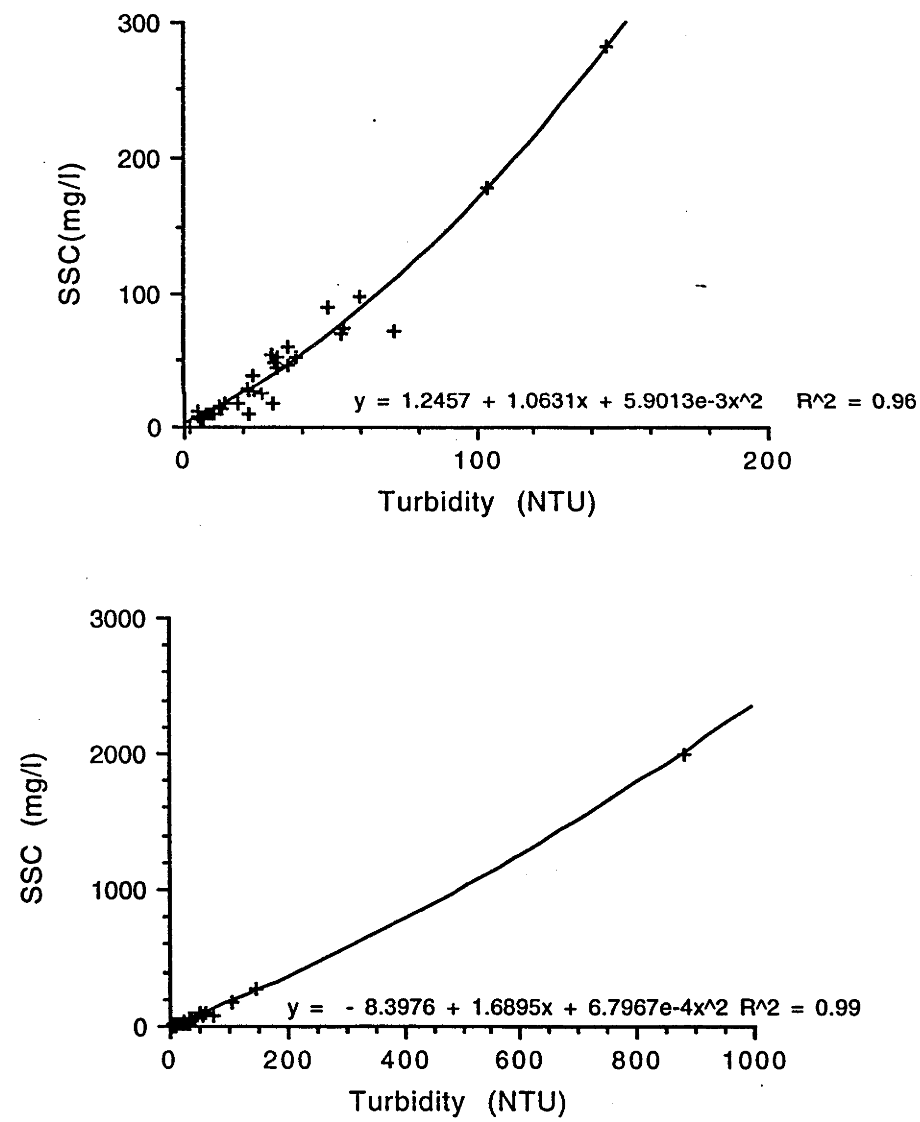


Fig. 3.4.1
Calibration curve for the relationship between turbidity (0-200 NTU (n=36; top); 0-880 NTU (bottom)) and suspended sediment concentration. (Samples from the Tully River catchment).

Turbidity measurements on the < 0.45 μm filtrate of 23 water samples from the Tully River and its tributary streams indicate that there is a significant, inverse relationship between the turbidity of the unfiltered sample and the proportion of that turbidity contributed by the < 0.45 μm fraction (Fig. 3.4.2). The most likely cause of this is clogging of the filter paper for samples with higher sediment concentrations, and therefore passing a smaller proportion of < 0.45 μm particles as the SSC increased.

For samples with turbidity < 5 NTU the mean percentage contributed by the filtrate is 27.4 ± 27.0 % (n = 8). When turbidity is > 30 NTU the filtrate contribution is only 3.1 ± 4.0 % (n = 7). An underestimate of total suspended load is implied but is potentially offset by:

i. The decline in sediment mass per unit turbidity as the particle size decreases, which in turn may be offset by a decline in instrument sensitivity at sub-micron particle sizes (Gippel, 1989).

ii. The proportion of < 0.45 μm turbidity which is contributed by water colour rather than particulates.

Uncertainities arising (additional to those of Eqn. 3.3) increase as turbidity decreases. At the higher turbidities associated with major runoff events (of greatest consequence in sediment yield and load studies) these uncertainities are minimal.

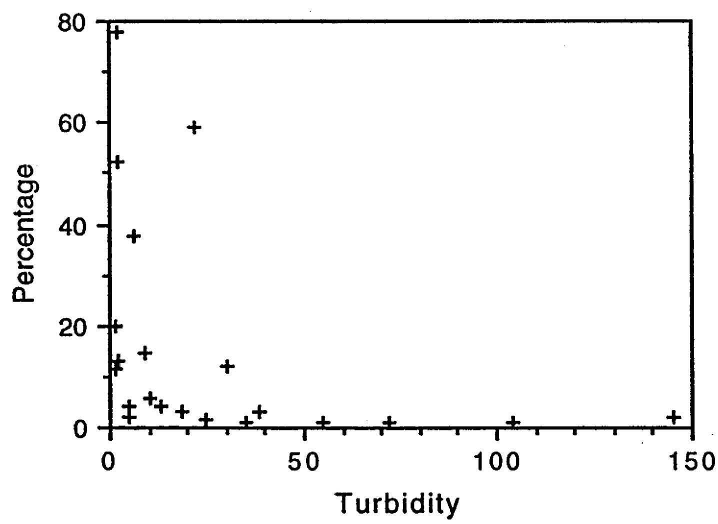


Fig. 3.4.2
Scatter plot showing the proportion of turbidity contributed by the < 0.45 μm filtrate in relation to the turbidity of the unfiltered sample.

The data set was subdivided into four subsets defined by sub-catchment (n=19,7,6,4) to examine the consistency of the turbidity and SSC relationship between subcatchments. The slope coefficients of linear regressions lie in the range 1.41 to 1.96 and R^2 is in the range 0.95 to 0.97 for these relationships, indicating that there is reasonable consistency in the relationship between SSC and turbidity within the Tully River catchment.

3.4.2 Calibration of conductivity with total dissolved solid concentrations:

TDS has a strong linear relationship with conductivity (Fig. 3.4.3) of the form:

TDS = 1.359 + 0.774. Conductivity (n=21; R^2 = 0.98) [Eqn. 3.4.3]

The range of data used to derive this relationship covers 67% of the range of conductivity observed in samples from the Tully River (Site 1). The relationship is significant and is used to derive the estimates of TDS used in the following pages.

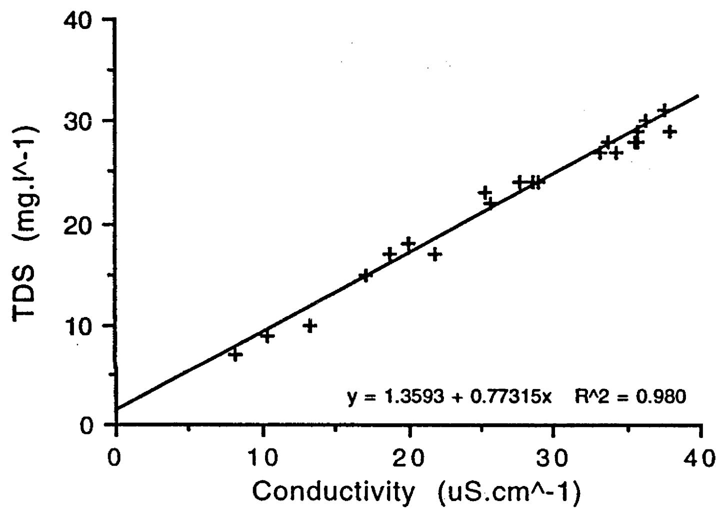


Fig. 3.4.3
Calibration relationship between conductivity and total dissolved solids. (Samples from Tully River catchment; n = 21)

3.4.3 Atmospheric accession rates:

The following brief outline of the distribution of cyclic salts in the Tully catchment is provided as background to the discussion of dissolved load in the Tully River (Ch. 3.6 and 3.7) and its tributaries (3.9 and 3.10).

The sampling method employed, using rainwater samples obtained from gauging stations where the receptacle was not cleaned before each event, means that the results presented are a better measure of total atmospheric accession than of precipitation solute concentration for a given event. The results are still relevant to the estimation of stream solute concentrations, but cannot be used to determine the true precipitation chemistry for a given rainfall event as samples will contain ions deposited in the receptacle by dry precipitation between events. White, Starkey and Saunders (1971) estimated that between 50 and 70 % of atmospheric accession is as dry precipitation.

Mean rainfall conductivity at Tully (18 km from the coast) during the sampling period was 26.6 $\mu S.cm^{-1}$ (s.d. 18.71; n=63) and at Cardstone (60 km inland) was 14.0 $\mu S.cm^{-1}$ (s.d. = 9.58; n= 45). Variation in rainfall conductivity is about the same at both sites (c.v = 70% and 68%, respectively). On the 42 days during the sampling period on which rainfall occurred at both sampling sites, the solute concentration of rainwater at Tully was significantly greater than at Cardstone (paired t - test; $p \leq 0.05$).

Multiple regression analysis of the relationship between the rainfall's conductivity and the variables *ln* (rainfall), time elapsed since the previous rainfall event and time elapsed since the commencement of the sampling periods was carried out. At both sites the rainfall solute load decreased with increased rainfall per event and increased with greater elapsed time between events. At both Tully and Cardstone rainfall solute concentration decreased over time as the frequency and magnitude of rainfall events increased from the dry to the wet season. The washing of salts from the atmosphere is a likely reason for this trend (Douglas, 1968). An additional factor here may be the decline, at times in excess of 50% (Wolanski and van Senden, 1983), in salinity of Rockingham Bay waters due to river discharges during the wet season (Chapter 5.3.2.2). All of the coefficients in these relationships are significant ('t'; $p \leq 0.05$) with the exception of the elapsed time since previous event factor at Cardwell. However, only 36% and 44% of the variance in rainfall conductivity at Tully and Cardwell, respectively, is explained. The provenance of the precipitation and the wind-direction prior to the rainfall event are also likely to be important factors (Gorham, 1958).

The rapid decline in atmospheric accession of solutes with distance from the coast has been documented in numerous studies. For example, Walker *et al.* (1981) observed a very rapid decline in atmospheric accession of nutrients within a few kilometres of the coast in a study at Cooloola, 1 500 km south of Tully. The solute concentration of rainfall also decreases with altitude as rainfall increases and the atmospheric concentration of cyclic salts declines (Bakalowicz (cited in Meybeck,1983)). These are likely to be significant factors in the Tully catchment.

The estimated accession rate (rainfall x solute concentration) for the period November, 1987 to March, 1988 is 55.5 $t.km^{-2}.yr^{-1}$ at Tully and 16.1 $t.km^{-2}.yr^{-1}$ at Cardstone. These rates are high by world standards. That at Tully is two orders of magnitude greater than measured by Cleaves *et al.* (1970) in a small catchment in Maryland, USA, and an order of magnitude greater than that estimated for precipitation in Wyoming, USA (Hembree and Rainwater, 1961), northern Pennines, England (Crisp, 1966), and the Lake District, England (White, Starkey and Saunders, 1971). By comparison with most of these sites, both Tully and Cardstone are relatively close to the coast with a wind regime dominated by onshore winds throughout the year. As a result, higher levels of both dry and rainfall precipated inputs than those reported are likely. Accession rates for the Tully catchment are also greater than those recorded by Brasell and Gilmour (1980) for sites only 100 km north.

A difference between the Tully catchment results and many other studies of atmospheric accession is that results presented here are estimates of total solute load derived from conductivity. They are not directly comparable with input rates estimated from determination of specific ion concentrations, which may omit ions shown to be of importance in other studies. Differences in the chemistry of streamwater and rainwater does mean that errors in the TDS / conductivity relationship are possible.

3.4.4 Runoff model:

A simple monthly runoff model was developed for the Tully catchment in order to extend the streamflow record beyond the short period available from the Euramo gauge to the period for which rainfall data are available. A monthly model was used as it is adequate in relation to the temporal resolution of the coral fluorescence record (Chapter 6.2). A monthly model does not have aresolution consistent with the time scale of individual events, whether sediment peaks, discharge peaks or sediment plume dynamics.

Monthly runoff for the period May, 1972 to June, 1987 was adequately predicted using a three parameter regression model of the form:

$$Q_i = a + b.R_i + c.R_{i-1} + d.E_i$$

where Q = discharge (Ml)

R = monthly rainfall (mm)

E = monthly mean daily pan evaporation (mm)

a, b, c, and d are constants.

The discharge predicted is that for the Tully River at Euramo gauging station (QWRC 113006A) which represents 88 % of the entire catchment. Rainfall is that for Tully Sugar Mill (032042). Greater modelling accuracy may have been obtained using a more sophisticated analysis of the spatial distribution of catchment rainfall, eg. weighted polygons or rainfall surface fitting (Hutchinson and Bischof, 1983), however, there is only one rainfall station with a continuous record > 50 years and other stations which have been operated at various times do not provide an even coverage of the catchment. Evaporation data (14 years) used is that for the South Johnstone Experimental Station (032037), 38 km north of Tully and climatically similar. Use of the mean monthly value allows evaporation to be incorporated into the model for the time prior to the commencement of recording. Much of the inter-annual variation in the monthly evaporation data is correlated with variation in rainfall which is already included in the model.

The conventional procedure of developing the model on one half of the data and then validating it on the other was not used as this would have allowed only 7 years of data on which to base the extrapolation to the 47 years without streamflow data.

Instead, three models were developed. Model 2 was based on the December, 1979-June,1987 data and validated on the May, 1972 - November, 1979 data. Model 3 was developed on the 1972-1979 data and validated on the 1979-1987 data. The statistical parameters pertaining to these relationships are given in Table 3.4.1 and show that an R^2 value of 0.88 was obtained for both model development and calibration relationships. Similarly, all coefficients were significant (t-test; $p < 0.05$), F-ratios were significant ($p < 0.05$) and standard errors comparable.

Parameter	Model 1	Model 2	Validation	Model 3	Validation
a	150 859	149 778		172 821	
b	602.3	557.4		649.5	
c	159.9	162.0		136.8	
d	-30 765	-28 887		-36 064	
n (mths)	182	91		91	
R^2	0.88	0.88	0.88	0.88	0.88
F probability	0.00	0.00	0.00	0.00	0.00
Std. Err.	88 333	76 000	76 248	98 501	98 257

Table 3.4.1
Statistical parameters for Tully River runoff model (monthly flows in ML) and validation tests.

Given the consistency of these results it was appropriate to develop an additional model (Model 1) based on the complete data sets. This approach provides both adequate validation and a more reliable model. 88 % of the variance in monthly discharge was again explained by Model 1 and all coefficients were significant (Table 3.4.1; Fig. 3.4.4). (For an even simpler model ($Q_i = a + b.\ R_i$), $R^2 = 0.81$.) Model residuals tend to increase with discharge, in contravention of the regression assumptions. Percentage errors decrease as discharge increases (Fig. 3.4.5), so that, for the 25 months with Q > 0.5×10^6 Ml, the mean error is 14.2 %. Although these 25 months represent only 14 % of observations for the period modelled, they contributed 42 % of the total discharge.

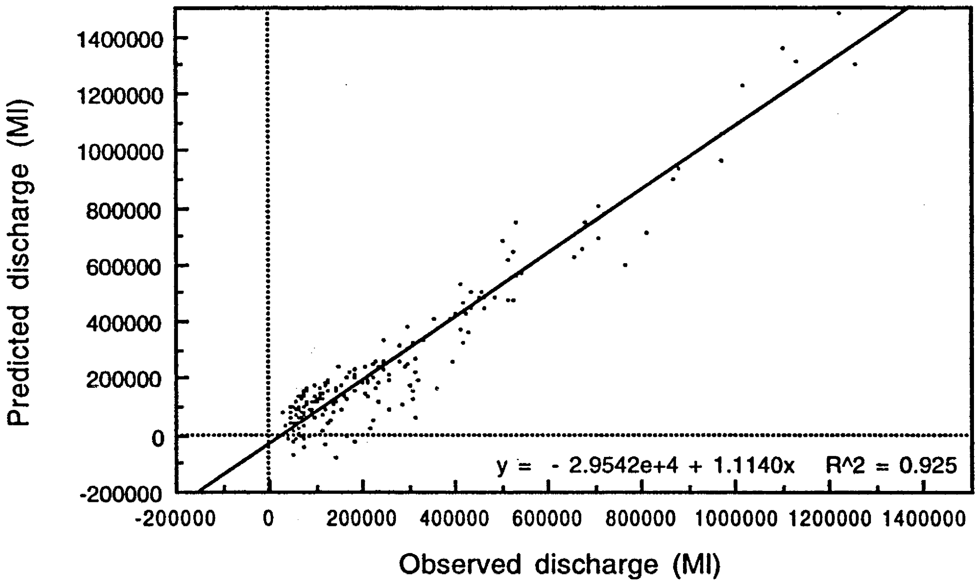


Fig. 3.4.4
Relationship between observed and predicted monthly discharges at Euramo using Model 1.

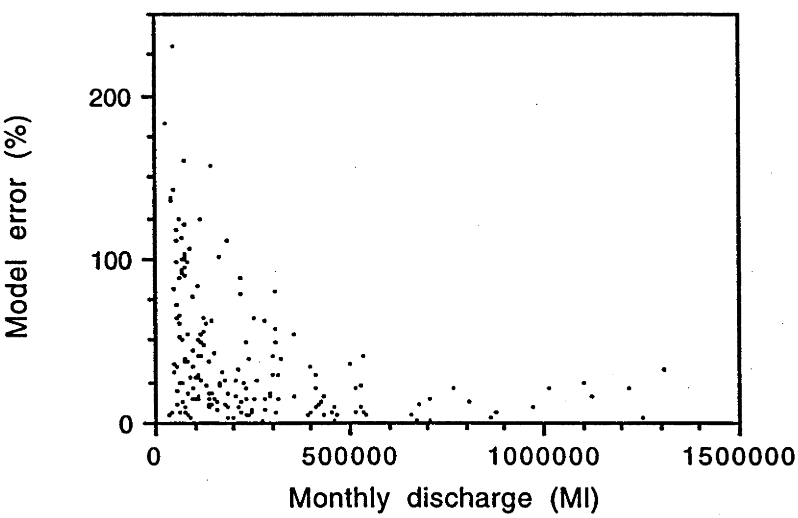


Fig. 3.4.5
Errors in monthly runoff prediction in relation to observed discharge (n=182 months).

Although there are inadequacies in the use of multivariate linear correlation for runoff estimation (Linsley *et al.*, 1975) the results for this model are encouraging. However, Tully River discharge can be better predicted using monthly discharge from the Herbert and Johnstone Rivers, for which there is > 60 years of data and for which the coefficients of determination of the correlation are 0.96 and 0.92, respectively, than by using the runoff model described above. No improvement in the coefficient of determination is obtained in a multivariate relationship using data from both of these streams.

3.5 SUSPENDED SEDIMENTS IN THE TULLY RIVER:

3.5.1 Tully River discharge during sampling periods:

During the first 98 days of the 1987-88 sampling period (30.10.1987 - 4.2.1988), discharge in the Tully River at Euramo was essentially baseflow (28.2 $\pm$ 3.3 cumecs; Fig. 3.5.1). A series of discharge peaks of 41, 115 and 380 cumecs occurred between the 8th and 13th of February, the peak discharge during this period having an exceedance time of 4 %. On 8.3.1988 another Q peak of 130 cumecs occurred (exceedance time = 20 %).

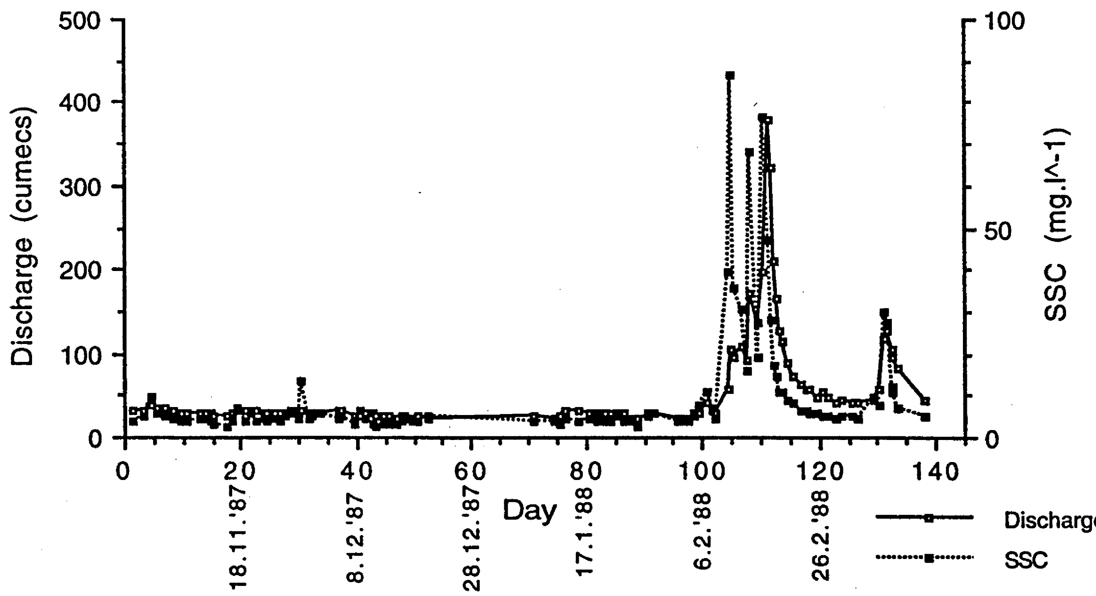


Fig. 3.5.1
Time series of discharge and SSC during the 1987-88 sampling period; n = 103.

Hydrological conditions during the March-April, 1990 sampling period were quite different from those during 1987-88. Between March 18 and April 12, 1990 river stage observations were made on 54 occasions spanning a discharge range of 34.9 to 950 cumecs. Unfortunately, the QWRC recorder failed during this event. Therefore, the only stage data available during the sampling period are those obtained at times of water sampling.

A time series of Q and SSC for the sampling period is given in Fig. 3.5.2 for the 1990 wet season. Prior to the commencement of rainfall on 19.3.1990, Q in the Tully River was 34.9 cumecs, a little higher (25 %) than the baseflow recorded for the 1987-88 observations. An initial rapid rise in the hydrograph to 485 cumecs (21.3.1990) was followed by a recession to 325 cumecs (22.3.1990). The persistence of cyclone *Ivor* as a tropical rain depression resulted in a further increase in Q resulting in an estimated maximum discharge of 1 000 cumecs at 04.30 on 24.3.1990. The time and magnitude of the peak discharge is estimated from information on river levels supplied by Euramo residents. The highest Q for which stage was measured at the gauging site was 950 cumecs at 18.00 on 24.3.1990.

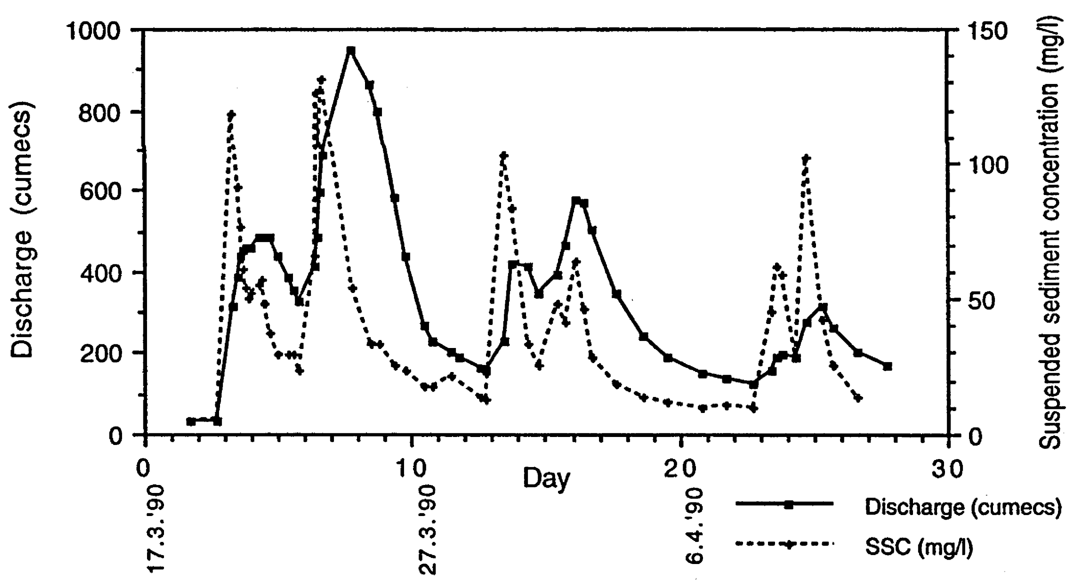


Fig. 3.5.2
Time series of discharge and suspended sediment concentration in the Tully River during the March - April, 1990 wet season.

3.5.2 Tully River suspended sediment concentrations - 1988 and 1990 wet seasons:

During the period October 30, 1987 to March 15, 1988, 103 water samples were obtained from the Tully River at Euramo. Turbidity and conductivity determinations were made on each of these samples and converted to SSC and TDS using Eqn. 3.4.1 and 3.4.3. The sampling period was chosen in order to monitor suspended sediment concentrations in the period of high erosion hazard prior to the onset of the wet season proper, and concentrations during the wet season months of January to March. As previously indicated, there were no significant rainfall events in the November - December, 1987 period and little rain fell in January. As a result, no inferrences can be made regarding the contrast in stream suspended sediment concentrations between the pre-monsoon and monsoon seasons. Sampling during the 1990 season was confined to the reliably wet months of March and April, so no pre-monsoon suspended sediment concentrations are available from this data set either.

Suspended sediment concentrations measured (1987-88) ranged from 2.3 to 86.8 $mg.l^{-1}$ ($\bar{x}$ = 9.7 $\pm$ 14.2). For the first 98 days of this period (64 observations) there was little variation in Q, and the consistency of the SSCs (4.5 $\pm$ 1.6 $mg.l^{-1}$ at baseflow) reflected this. A slight decrease in Q over this period is paralleled by a decrease in SSC.

The flood peak of 380 cumecs on 17.2.1988 was preceded by two minor peaks, each of which was accompanied by an increase in SSC. After the peak of 17.2.1988, discharge decreased to a level 1.4 times greater than baseflow. At this time SSC had decreased to about the same level as for base flow. There is a relatively small SSC peak (30.2 $mg.l^{-1}$) in relation to Q (127.6 cumecs) on 8.3.1988.

Hydrological conditions during the March-April, 1990 sampling period were quite different from those during 1987-88, due to the influence of tropical cyclone *Ivor*. Between March 18 and April 12, 1990 a further 54 samples were obtained from the Tully River spanning a discharge range of 34.9 to c. 1 000 cumecs. The maximum stage during this period is equal third ranked in flood magnitudes for the Tully River this century. Sediment concentrations during this period ranged from 5.3 to 130.9 $mg.l^{-1}$ ($\bar{x}$ = 45.0 $\pm$ 32.2). The initial Q and SSC values recorded are a little higher than the baseflow means recorded for the 1987-88 observations. The pattern of SSC in relation to Q is illustrated in Fig. 3.5.2 and indicates a generally similar relationship to that observed during the discharge peaks of 1987-88.

During the March - April, 1990 study period there are six peaks in river discharge which are grouped into three events, each of which exhibits an initial rise in Q, a slight fall and then an increase in Q to the event maximum (Fig. 3.5.2). Peak discharges and suspended sediment concentrations are given in Table 3.5.1.

Event #	Peak #	Date of Q peak	Q (cumecs)	SSC ($mg.l^{-1}$)
1	1a	21.3.1990	487	118.9
	1b	24.3.1990	950	130.9
2	2a	30.3.1990	417	103.1
	2b	2.4.1990	572	63.9
3	3a	9.4.1990	195	61.8
	3b	11.4.1990	313	102.3

Table 3.5.1
Characteristics of Q and SSC peaks during March - April, 1990.

Suspended sediment concentrations in the Tully River are strongly correlated with discharge (Fig. 3.5.3). The relationship between SSC and Q for all observations (1987-88 and 1990) is:

$SSC = 0.255 \,.\, Q^{0.858}$ (n = 157; $R^2 = 0.81$)

and, disaggregated by stage (Fig. 3.5.4):

$SSC = 0.222 \,.\, Q^{0.945}$ (rising stage; n = 72; $R^2 = 0.85$)

$SSC = 0.364 \,.\, Q^{0.727}$ (falling stage; n = 85; $R^2 = 0.88$)

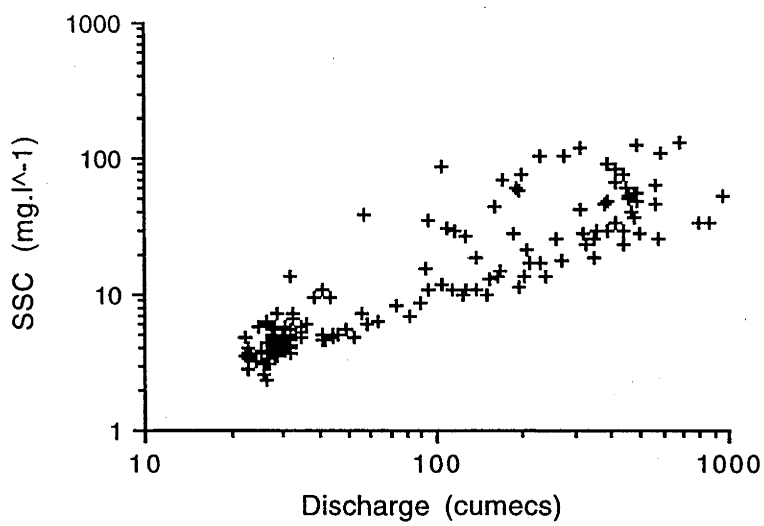


Fig. 3.5.3
The relationship between discharge and SSC in the Tully River, 1987-88 and 1990 sampling periods; n = 157.

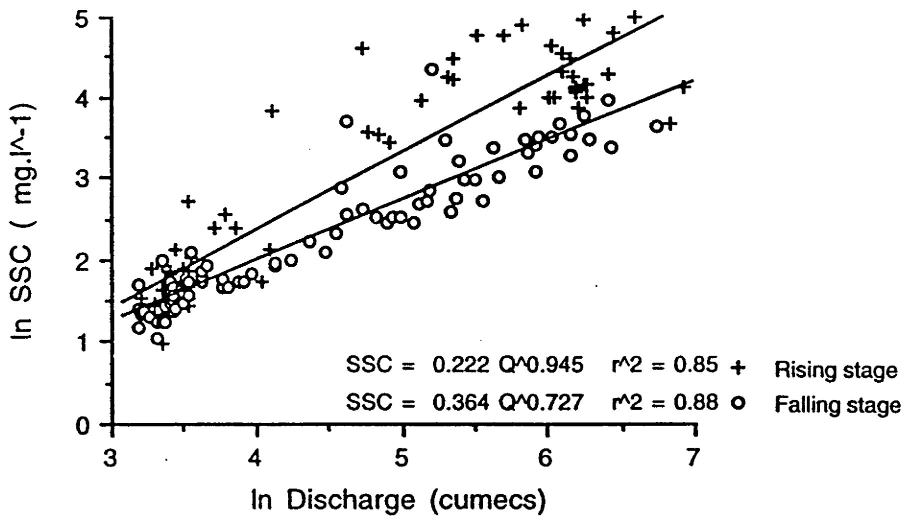


Fig. 3.5.4
The relationship between SSC and discharge for rising and falling stage in the Tully River; (n = 72 (rising); n = 85 (falling)).

As is suggested by Figs. 3.5.1 and 3.5.2, the relationship between SSC and Q is strongly hysteretic (Fig. 3.5.5), with much higher sediment concentrations occurring during rising stage than during recession. This characteristic of sediment/discharge relationships is commonly observed, although anti-clockwise hysteresis has been reported (eg. Geary, 1981; Klein, 1984). Because cleared areas in the Tully catchment are close to the gauging station and the upstream areas are generally undisturbed rainforest the hysteresis is likely to be greater than would be the case in the natural system.

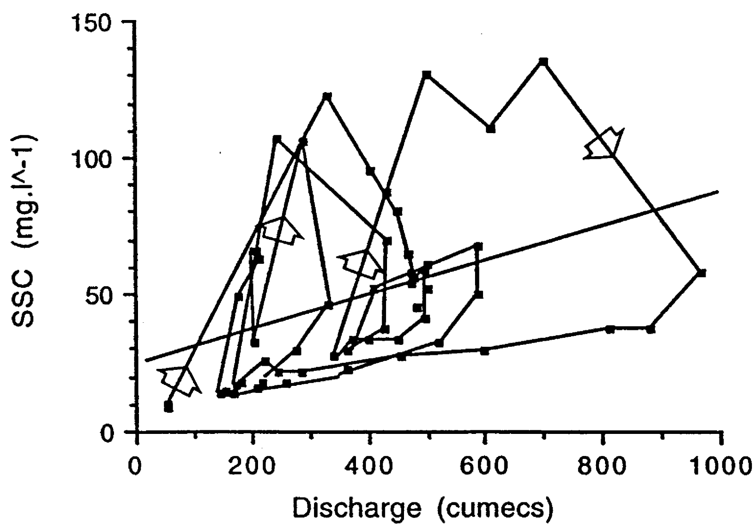


Fig. 3.5.5
Hysteresis in the relationship between discharge and SSC in the Tully River during March - April, 1990; n = 54.

Comparison of the relationship between Q and SSC for different time periods (Fig. 3.5.6) shows that marked differences are apparent in the slope of the rating curve and in the strength of the relationship. These differences, even in a catchment of low inter-annual stream flow variability, are a caution against application of data for a single season of observation in order to estimate long-term average sediment yield.

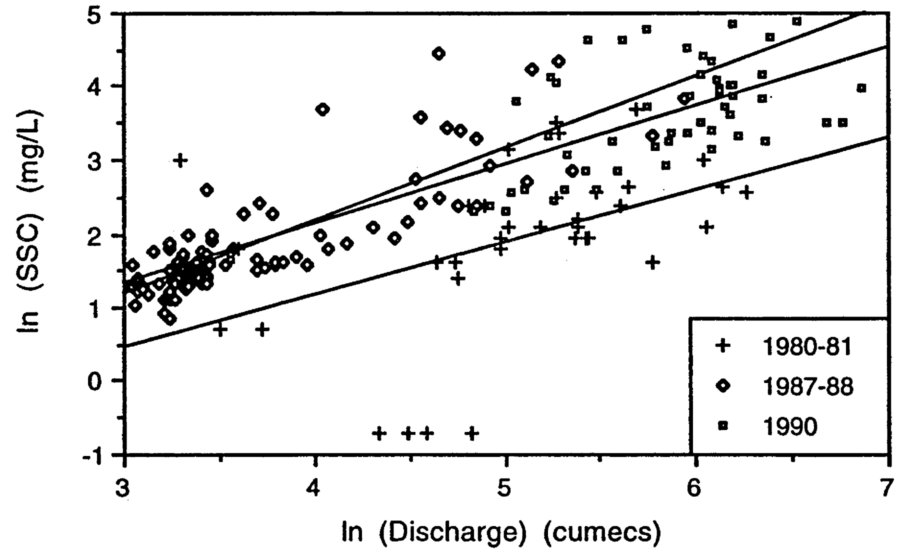


Fig. 3.5.6
Inter-annual comparison of the relationship between discharge and suspended sediment concentration in the Tully River.
1980 - 81:- ln (SSC) = 0.708.ln (Q) - 1.680; $R^2 = 0.20$ (QWRC data)
1987 - 88:- ln (SSC) = 0.979.ln (Q) - 1.772; $R^2 = 0.72$
1990:- ln (SSC) = 0.798.ln (Q) - 1.057; $R^2 = 0.44$

3.5.3 Suspended sediment concentrations in the Tully River - some regional and global comparisons:

The suspended sediment concentrations recorded during this sequence of runoff events are similar to that documented by Douglas (1977; 116) for the Barron River (at Picnic Crossing; catchment area = 225 km^2) during the passage of cyclone 'Flora' in December, 1964. Prior to this event SSC was about 6 - 10 $mg.l^{-1}$, rising rapidly to peak at about 160 $mg.l^{-1}$. Suspended sediment concentrations in the Tully River are slightly lower than for the Barron, both prior to runoff and at the SSC peak. On the other hand, the Herbert River, the next major river to the south of the Tully, has much higher sediment concentrations than the Tully. Of 40 observations by the Queensland Water Quality Council (unpublished data) the maximum was 450 $mg.l^{-1}$ and eight observations on different days over a six month period (including the 1981 floods) exceeded the maximum recorded for the Tully during the 1990 floods. A peak SSC in the Burdekin of c. 2 500 $mg.l^{-1}$ is indicated by Belperio (1979) and comparison of the Burdekin sediment rating curve with that for the Tully indicates that the Tully is about an order of magnitude lower over the entire range of stream flow. Belperio (1983) presents data illustrating the latitudinal variation in sediment yield of streams discharging to the Great Barrier Reef lagoon. In preparing this diagram, he has assumed that the sediment rating curve for the Burdekin is appropriate for all streams. The results outlined above indicate clearly that this is not the case.

The pattern of latitudinal variation in suspended sediment concentrations along the Queensland coast is likely to be strongly influenced by the climatic regime in individual catchments, particularly by annual precipitation, modified by the seasonality of the precipitation. Consequently, the pattern along the Queensland coast is likely to be one of high SSC from the strongly seasonal, low rainfall catchments on eastern Cape York Peninsula, decreasing southward in the higher rainfall areas, particularly from the Daintree River south. Of the major rivers, the lowest SSCs are likely to occur between the Barron and the Tully, with the likelihood that the sediment yield will be lowest where the proportion of catchment in the relatively dry hinterland is lowest. South of the Tully catchment, conditions become increasingly similar to those of Cape York, with increasing sediment concentrations the result.

The dominant influence on regional sediment yield patterns is clearly climatic, as Douglas (1973: 63) recognised - "While it is possible to demonstrate that human interference is important within a single catchment area by comparing two stations on the same river, man's activity does not appear to be as important as the climatic contrasts over the area as a whole." This is also, in part, because all of the major catchments have been subjected to some form of human modification, particularly beef cattle grazing in the drier areas and sugar cane cultivation where rainfall is high.

Within north Queensland, the Tully catchment is notable for its low suspended sediment concentrations. This appears to be a result of tectonic stability, low inter-annual rainfall variability (although seasonality is quite strong), all of the catchment lying in the high rainfall area, relatively low soil erodibility and the almost complete absence of land clearing on steeplands.

Douglas (1977; 118) tabulates exponents for suspended sediment relationships of the form $SSC = a.Q^b$ for streams in the Sungai-Kelang catchment in Malaysia. These catchments range from 0.6 to 1196.6 km2 in area with a wide variety of land uses including urban, construction and mining. The exponents range from 0.92 to 2.81. The exponent for the Kelang at Puchong (1197 km^2 in area, similar to the Tully, and including the wide variety of land use described) is 1.18. Douglas invites comparison with general statements of the exponent value such as that of Graf (1971) who suggested a range from 2 to 3 for streams in the western U.S.A.. By comparison, the exponent for the Tully River (0.86) is quite low.

3.5.4 Discharge lags and sediment depletion:

Glover and Johnson (1974) have suggested that the logical definition for the lag time would be the delay between the start of the rise in discharge and the change in concentration of the water quality parameter under investigation. They recognise the difficulty in determining these points on the hydrograph and chemograph and instead use the times at which 50 % of the total change in discharge and in concentration occur. The times of peak discharge and peak concentration are used herein because the sampling intensity was increased at the beginning of each event, so the times of the peaks are likely to be the most accurate.

Suspended sediment concentrations in the Tully catchment are responsive to changes in stream flow conditions and a peak in SSC occurs in relation to each Q peak. In each case the Q peak lags, or occurs at the same time as, the SSC peak, with an average lag during the 1990 wet season of 11 hours (Table 3.5.2). The accuracy of this estimate of the lag is constrained by the frequency of sampling (one every 11.6 hours on average (1990), although the sampling frequency was increased during periods of hydrological activity).

Within-event sediment depletion occurred consistently. For each discharge peak during the 1988 and 1990 wet seasons (Figs. 3.5.1 and 3.5.2 respectively) the sediment load declined markedly before the maximum Q was reached. In order to disassociate lag effects from sediment depletion, the time series of Q and SSC was interpolated at 3 hourly intervals, the lag correlation coefficients derived and hysteresis loops for each peak, corrected for lag, were plotted. It is clear (Fig. 3.5.7; 1990 events) that SSC on falling stages (after removal of the Q lag) is much lower than on rising stages, consistent with depletion of sediment supply during the event.

Between-event sediment depletion was investigated by comparing the area under the hydrograph with the area under the sedigraph for each event and by comparing SSC and Q peak heights for each Q peak (Table 3.5.2). There is no evidence of between-event sediment depletion.

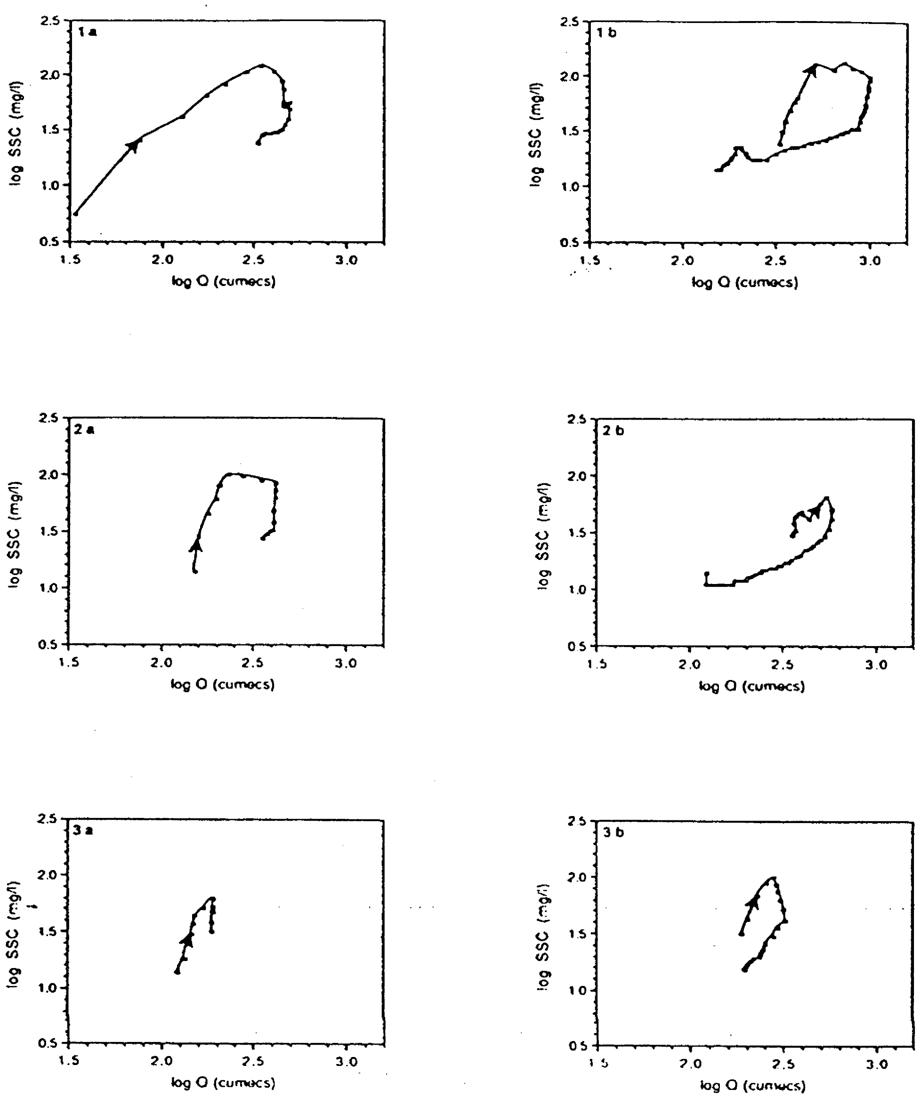


Fig. 3.5.7
Hysteresis loops for individual flood peaks (1990 data) corrected for lag of the discharge peak.

Event #	Peak #	Lag time (days; SSC->Q)	SSC:Q (peak area)	SSC:Q (peak height)
1988 data				
1	1a		0.66	0.94
	1b			0.82
	1c			0.73
2			0.55	0.70
1990 data				
1	1a	1.05	0.60	0.77
	1b	0.47		0.70
2	2a	0.33	0.56	0.77
	2b	0.0		0.65
3	3a	0.16	0.66	0.78
	3b	0.68		0.80

Table 3.5.2
Lag times, peak area and peak height relationships between SSC and Q.

The spatial pattern of rainfall also plays a role in the SSC v Q relationship. Fig. 3.5.8 shows that, as the proportion of rainfall which occurs at Cardstone (40 km inland) increases in relation to that at Tully, the SSC:Q ratio (for both peaks and events) decreases, as does the slope of the SSC v Q (rising SSC) regression line (Fig. 3.5.9). These results demonstrate the influence of spatial characteristics of rainfall on the SSC v Q relationship. They also indicate that washload concentrations from the upper reaches of the catchment are lower than from the lower reaches, as there is less sediment in relation to discharge as the proportion of runoff waters derived from the upper reaches increases.

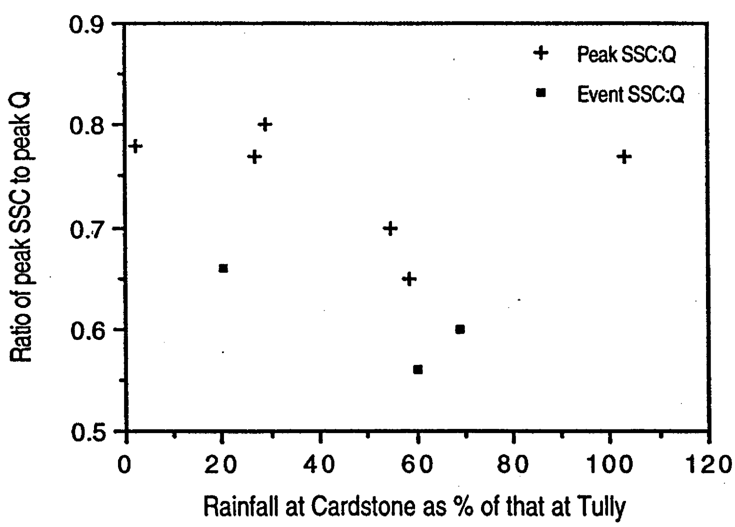


Fig. 3.5.8
Relationship between the SSC:Q ratio (peaks and events) and the percentage of rainfall occurring at Tully which occurs at Cardstone.

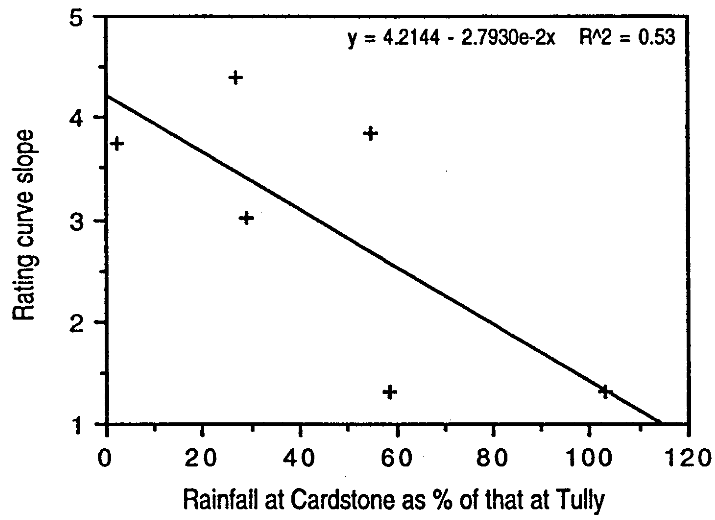


Fig. 3.5.9
Relationship between the rising SSC rating curve slope and the percentage of rainfall occurring at Tully which occurs at Cardstone.

An additional factor in the relationship between SSC and Q, which may contribute to hysteresis in the relationship with or without lag correction, is hysteresis in the relationship between SSC and turbidity. Gippel (1989; 150) notes that gilvin concentration in streamwaters increases markedly at the commencement of a runoff event and then gradually declines, irrespective of subsequent rainfall. As a result, clockwise hysteresis between SSC and turbidity is likely as gilvin constitutes a greater proportion of the measured turbidity early in the event. In practice, Gippel (1989; 172) found that clockwise hysteresis occurred in only five of ten events monitored. Given the spectral characteristics of gilvin absorbtion and the wavelength at which the Analite nephelometer operates (Chapter 3.2.3), this factor is expected to be quite insignificant in this data set.

3.5.5 Characteristics of Tully River suspended sediments:

3.5.5.1 Mineralogy:

X-ray diffractograms of Tully River suspended sediments (Fig. 3.5.10) show that the major mineral species are kaolin and quartz with smaller quantities of chlorite, illite (hydromicas) and plagioclase and K-feldspars. The nature of the mineral assemblage is generally consistent with that of the soils of the catchment (Murtha, 1986; 1992), and that expected from the intense leaching and weathering regime of the wet tropics (Douglas, 1977: 42; Paton, 1978: 43).

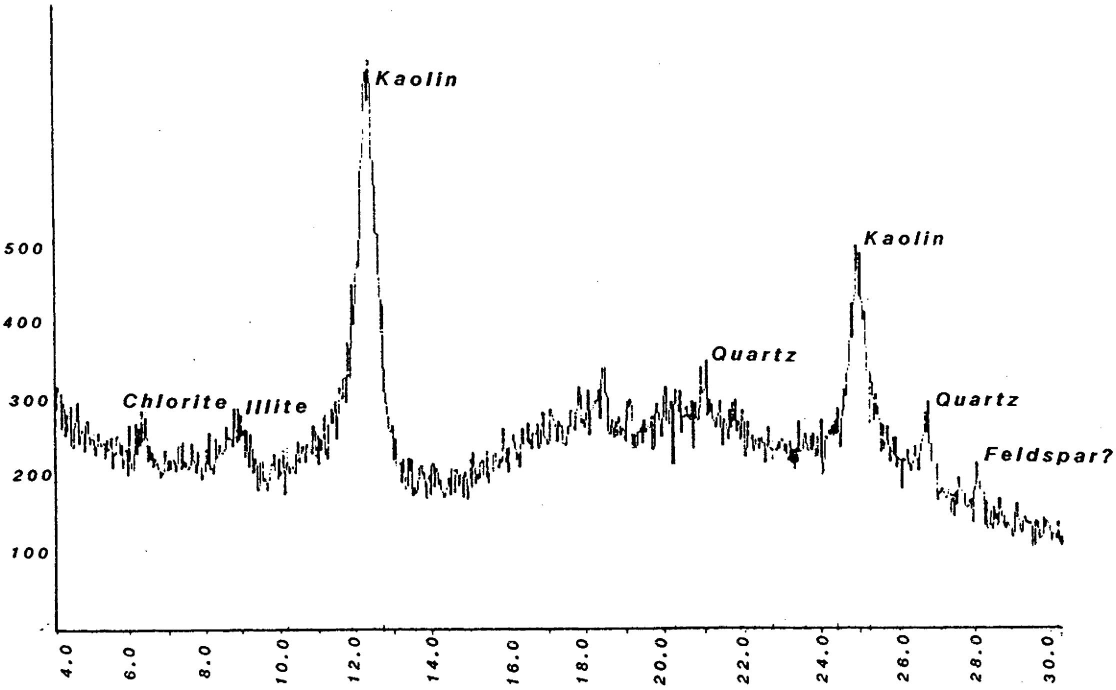


Fig. 3.5.10
X-ray diffractogram for Tully River suspended sediments sampled on March 27, 1990.

Estimates of quantities of mineral constituents cannot be accurately derived from these data because of differences in such characteristics as mass absorbtion coefficients. However, variation in the intensity ratios of the major minerals could indicate systematic changes in, for example, energy regimes and sediment source areas. The relatively consistent mineralogy of the soils (Murtha, 1986) makes it unlikely that sediment sourcing using XRD analysis will be successful in the Tully catchment, although it has been used elsewhere with varying degrees of success (eg. Lund *et al.*, 1972; Klages and Hsieh, 1975; Wall and Wilding, 1976). It was hypothesised that the relative proportions of kaolin and quartz would vary with streamflow, coarse-grained quartz particles forming a greater proportion of the load as discharge increased. Such a pattern could have implications for the relationship between river-borne sediments and those actually reaching the coral growth sites. Furthermore, the geochemical characteristics of sediments change with mineralogy and these changes may be of importance in the sediment-associated transport of, for example, nutrients and heavy metals.

Ratios of kaolin to quartz peak heightswere regressed against discharge (Fig. 3.5.11) and mineralogical composition of the sediments was found to be independent of Q, and was also unrelated to the SSC of the sample (Fig 3.5.12). Given the common generalisation of quartz minerals being relatively coarse by comparison with clay-sized kaolin, the absence of any relationship between mineralogical composition and discharge is surprising, but is probably a result of sampling washload from the top of the water column.

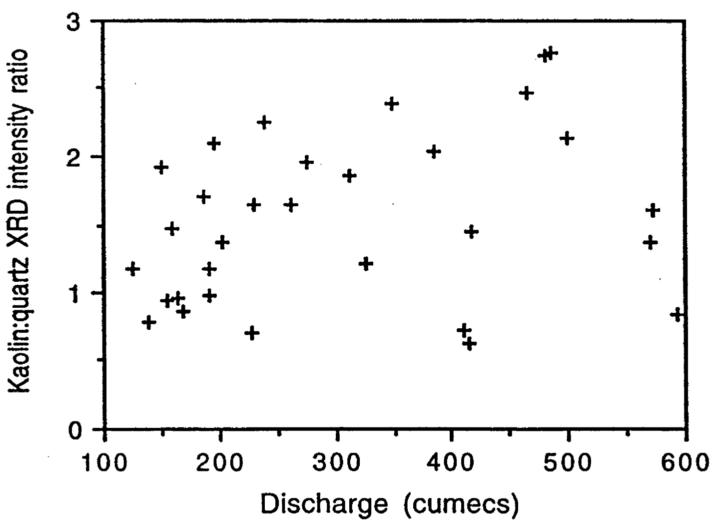


Fig. 3.5.11
Kaolin:quartz peak height XRD intensity ratio in relation to discharge; Tully River samples.

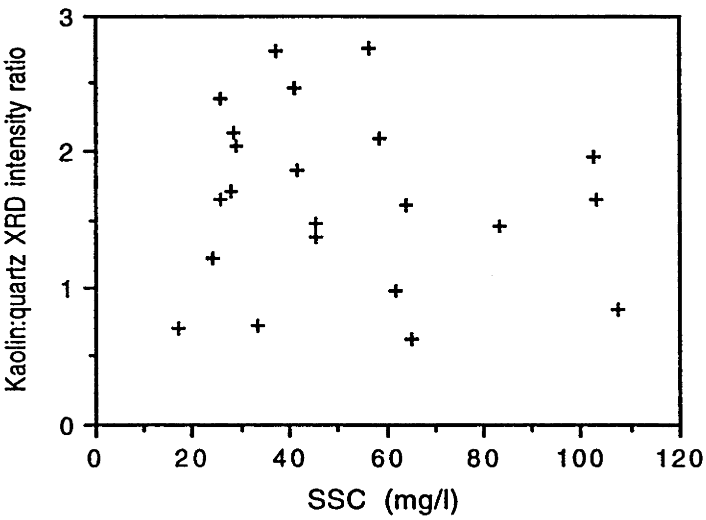


Fig. 3.5.12
Kaolin:quartz peak height XRD intensity ratios in relation to SSC (> 20mg.l^{-1}); (Tully River samples, n = 21).

Given the limitations of quantitative XRD analysis and the fact that XRD peak heights for individual mineral species were strongly related to the mass of sediment on the filter paper (see Gippel, 1989), no attempt was made to undertake a more thorough mineralogical analysis. However, the results presented indicate that there is no significant variation in mineralogy in relation to changes in either streamflow or suspended sediment concentration, and that there is little prospect for mineralogical sediment sourcing in this catchment. An advantage of this mineralogical consistency is the absence of a mineralogical effect on the turbidity determinations (Chapter 3.1.1).

3.5.5.2 Particle size:

Particle size distributions (Fig. 3.5.13) of Tully River suspended sediments were determined on nine samples obtained between 7.4.1990 and 12.4.1990, at discharges in the range 126 - 313 cumecs and SSC in the range 10.1 - 102 mg.l^{-1}. Median particle sizes ranged from 3.2 to 14.8 μm. There is no correlation between median size and either Q or SSC, nor is their any pattern of particle size hysteresis in relation to these variables.

The coarsest particles are probably spurious, a problem of the Horiba instrument noted by Gippel (1988). No sand-sized particles (> 63 μm) were detected in any of the samples, and particles in the range 40 - 60 μm were detected in only four of the nine samples and were always < 25 % of the total. Thus, suspended sediments in the Tully River lie within the geochemically active (< 63 μm) particle size range in which suspended sediments play a critical role in the transport, deposition and remobilisation of nutrients, heavy metals, polychlorinated biphenyls and non-ionic organochlorine pesticides (Ongley *et al.*, 1982).

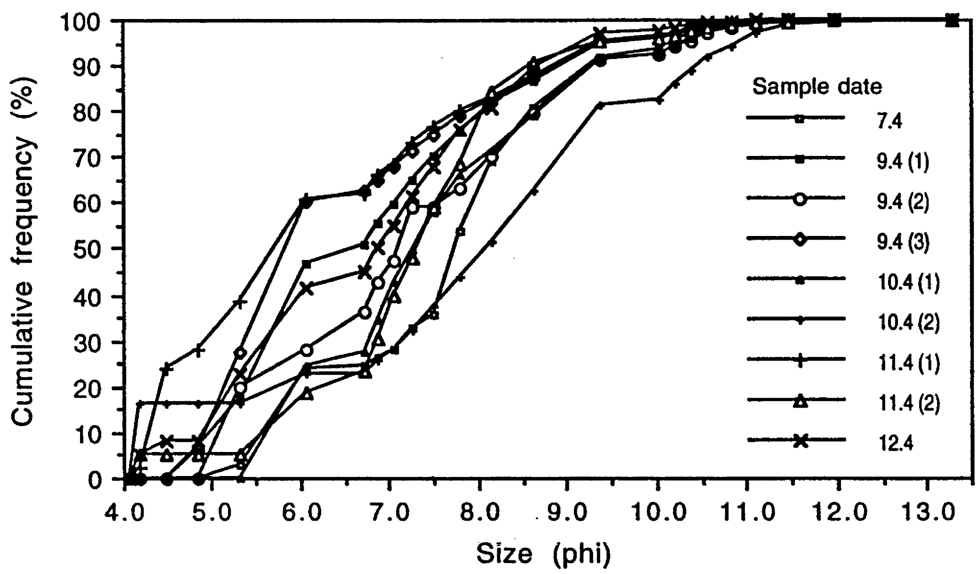


Fig. 3.5.13
Cumulative distributions of Tully River suspended sediment samples.

Accurate determinations of the clay-sized (< 2 μm) fraction are not possible because particle size distributions were determined on sediments resuspended from 0.45 μm filter papers. Close examination of the distribution patterns in the < 2 μm size range shows that there is no discontinuity at the filter paper pore size. Therefore, it seems likely that the particle size distributions are not significantly biased by loss of clay-sized sediments through the filter papers. The mean clay-sized fraction is 17.5 ± 8.5 % (n=9) and the suspended load is predominantly fine to medium silt.

Paton (1978:44) suggests that the intense weathering and leaching regimes of the wet tropics are likely to result in bimodal particle size distributions in soils with a quartz peak (> 20 μm) and a clay mineral peak (< 2 μm). The Tully River suspended sediments reflect this generalisation in the < 2 μm fraction, although the silt fraction in the suspension is much finer than the suggested > 20 μm in the soil.

The absence of any sand-sized particles from the suspended sediment samples, the observation that the < 63 μm fraction is generally well mixed (Colby, 1963; Belperio, 1979; Ongley, *et al.*, 1982) and the fact that stream velocities are relatively low close to the stream bed combine to suggest that, in the Tully River, little error is induced by point sampling close to the water surface. As a result, no correction is required for vertical SSC gradients when calculating river loads. The general consistency of particle size distributions, the size range observed and the absence of any relationship between particle size and Q or SSC suggests that there is little particle size effect on the turbidity determinations (Chapter 3.1.1).

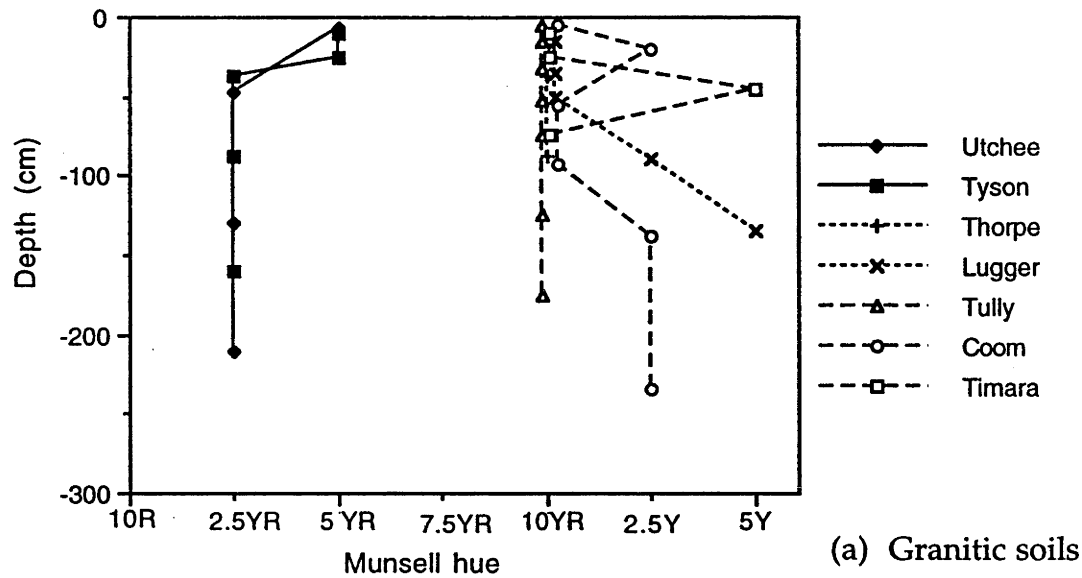
3.5.5.3 Colour:

Field observations during rainfall/runoff events indicated that systematic variation in the colour of suspended stream load could be an indicator of variation in the source of sediment during an event. The pattern observed was of brown or reddish suspensions during rising stages and creamy or yellowish sediments during falling stages. This general pattern was also observed in tributary streams of the Tully River and other catchments with similar soils and climate north to the Johnstone River. Qualitatively, this pattern was consistent with red sediments from montane and colluvial soils predominating in the rising stage sediments with yellower alluvium, streambank and subsoils the major constituent of falling stage and baseflow sediments. Given the marked colour contrast between these two soil and sediment types in wet, tropical regions, it seems likely that sediment colour could provide a simple sediment sourcing tool for these areas.

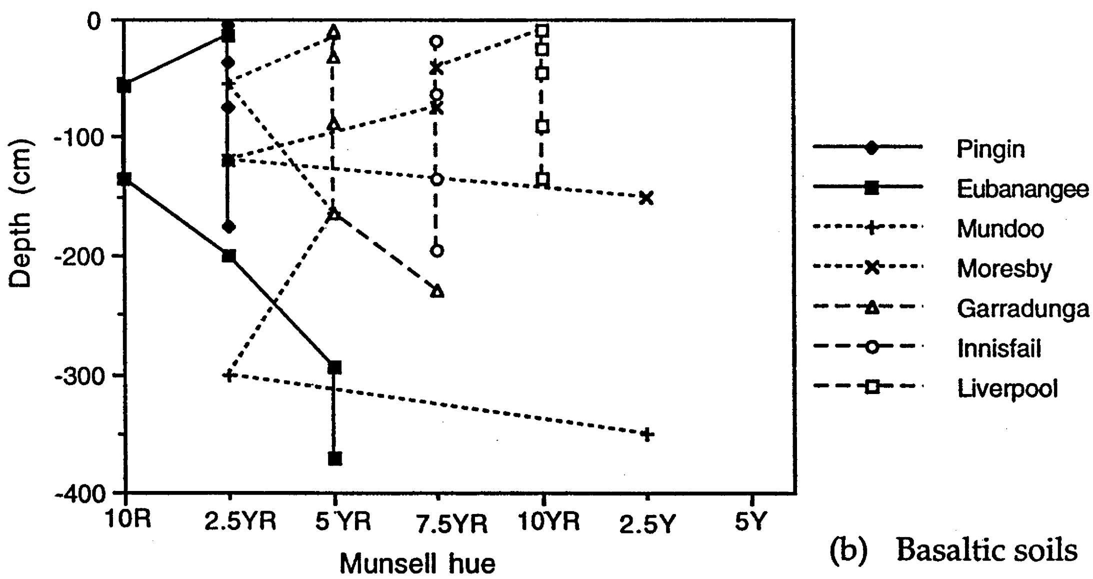
In order to further investigate this possibility, two approaches were tried. Firstly, absorbtion spectra were obtained for suspensions derived from colluvial and alluvial subsoils. Use of subsoils eliminated the effect of organic matter colour on the spectrum. Although the soil colours were markedly different to the human eye, there was no consistent pattern within the spectra which clearly discriminated the two soil types. In the absence of suitable equipment, this line of investigation was discontinued.

The second approach used was to quantify suspended sediment colour using the Munsell colour chart. Munsell colours (hue) for soils in the area (from Murtha, 1986) are shown in Fig. 3.5.14. They show clearly the contrast between montane/colluvial, alluvial fan and alluvium soils, and a less clear contrast between topsoil and subsoil. For soils derived from granitic parent material the surface horizon of montane/colluvial soils has a hue of 5YR which tends to redden with depth. Alluvial fan and alluvium surface soils generally have 10YR hues. A hue of 2.5Y or yellower is found only in subsoils of alluvial fans and alluvium. The hues of soils derived from metamorphics are very similar to those from granites. The pattern in basalt derived soils is similar, although these soils tend to be much redder. *In situ* top soils are 2.5YR, alluvial fan and alluvium soils are in the 5YR to 10YR range and their subsoils reach a hue of 2.5Y in only two samples.

Munsell colours of residues on 0.45 µm filter papers were determined for 42 Tully River water samples from the 1990 sampling period. Because there is a degree of subjectivity in Munsell colour determination, samples identified only by codes were analysed, in order that no bias be induced.

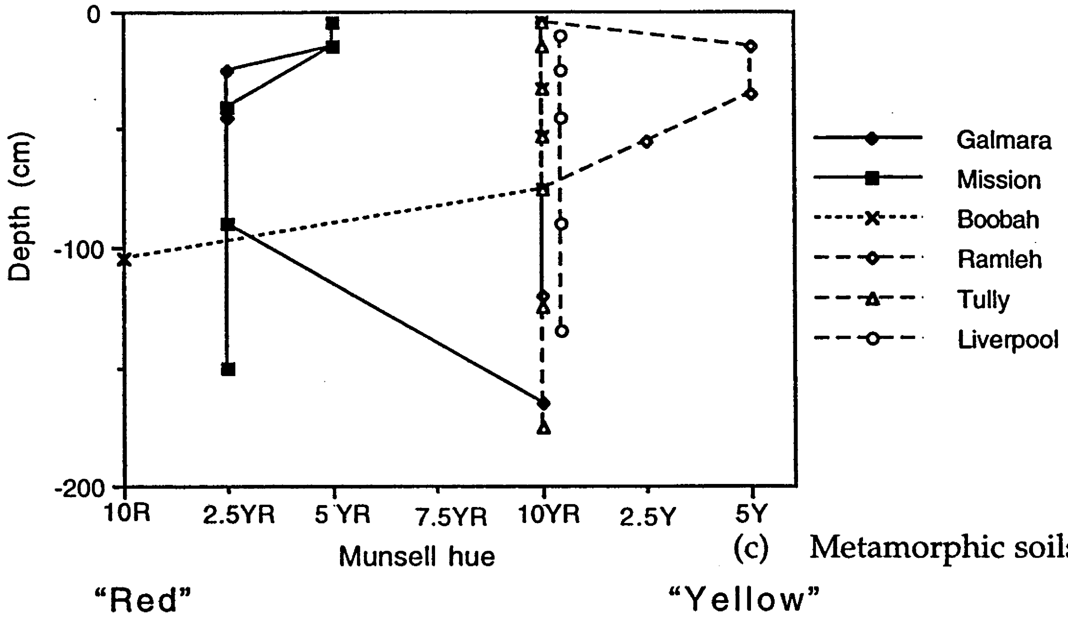


(a) Granitic soils



(b) Basaltic soils

Continued over



(c) Metamorphic soils

Fig. 3.5.14
Soil hue for profiles in the study area (Data and nomenclature from Murtha, 1986). Note: i. Descending order in legend is descending order in catenary sequence. ii. —— montane/colluvial soils; ······ alluvial fans; - - - - alluvium.

Fig. 3.5.15 shows the strong, significant relationship between the hue of the suspended sediment and the SSC, with reddish sediments in suspension at times of highest sediment concentrations and yellowish sediments at lower sediment concentrations. Fig. 3.5.16 illustrates the characteristics of sediment hue in relation to discharge. During rising stages the suspended sediments are reddish, during falling stages they are yellowish. The pattern is consistent with the preliminary field observations and with the hypothesis that montane, colluvial soils form a greater proportion of suspended load during rising stages.

Given that soils on or derived from granite predominate in the Tully catchment and that Munsell hues for soils from metamorphics and basalts exhibit generally similar patterns, the characteristics of the suspended sediment hues are contrasted with those for granites (Fig. 3.5.14(a)). If it is assumed that the NFR hue is directly related to the relative proportions of sediment from montane, colluvial and from alluvial sources, a crude estimate of the sediment provenance over a range of SSCs and Qs can be estimated. Based on the characteristics of NFR hues in relation to SSC and Q in Figs. 3.5.15 and 3.5.16 respectively, it is concluded that, at peak SSCs as much as half of the suspended load may be derived from *in situ* montane and colluvial soils, most of which are still under relatively undisturbed rainforest and cover c. 73 % of the catchment (mapped from the 1:250 000 geological sheet). During hydrograph recession and at low streamflows (times of low SSC) sediments derived from alluvial subsoils (by bank erosion and collapse and/or subsurface flow) are the main constituent of the load.

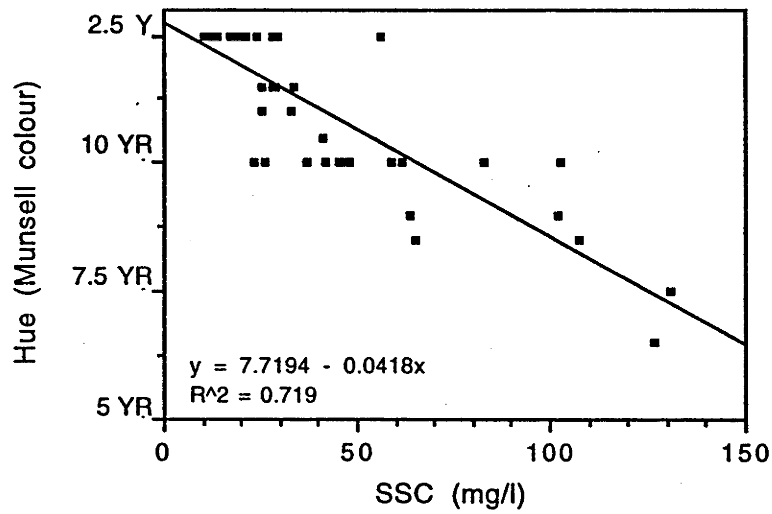


Fig. 3.5.15
Suspended sediment hue in relation to SSC;
Tully River filter paper samples (n=42).

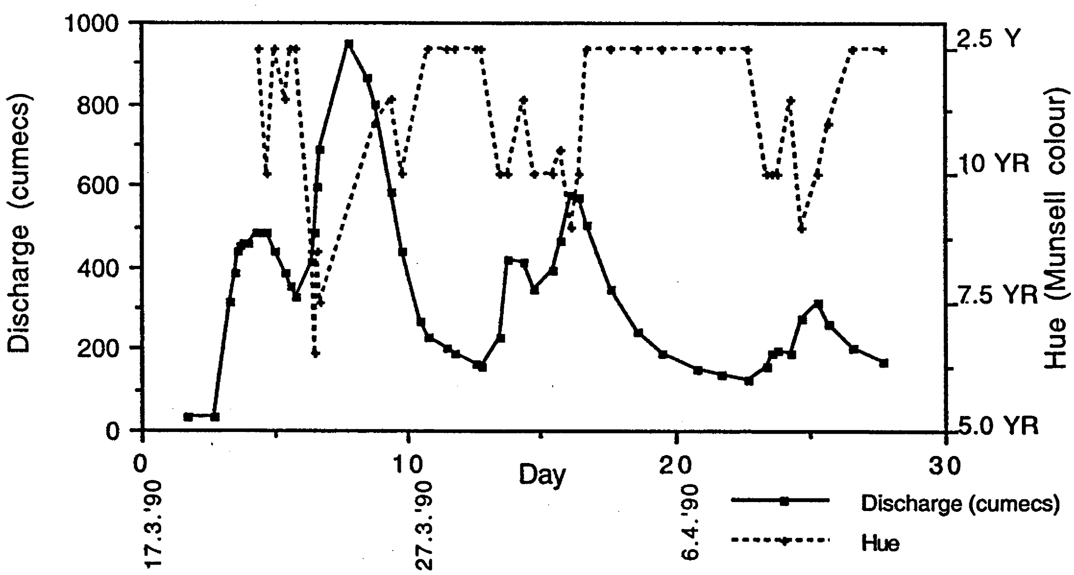


Fig. 3.5.16
Time series of suspended sediment hue in relation to discharge;
Tully River samples.

These results indicate that suspended load characteristics vary considerably during runoff events but appear to be correlated with the sediment concentration rather than the discharge. At high SSC (during rising stage) sediments include a high proportion of washload due to sheet erosion of which about half may be derived from the montane and colluvial soils of the catchment. Most of the remainder is probably derived from the alluvial fans and floodplain alluvium.

It is likely that organic matter content plays some role in variation of SSC colour. Soil colour is generally correlated with organic matter content, although Gippel (1989) states that DOC was not correlated with SSC (in Geebung Ck, NSW) and in the Tully River there is a strong correlation between colour and SSC (Fig. 3.5.15). Furthermore, the fact that SSC hues are often redder than those for alluvial plain topsoils also supports a sediment source explanation based on colour, rather than an explanation based on organic matter content.

The patterns of variation in sediment colour, correlated with SSC but not with Q, have implications for estimates of the sediment yield response to land use change and for the nature of sediments transported across Rockingham Bay to the adjacent fringing reefs. The results suggest that, in spite of c. 20 % of the catchment being cleared (about 8 % under crops), the rainforest-clad montane and colluvial soils continue to supply a large proportion of the wash load. Furthermore, the elemental composition of the sediments transported to and across Rockingham Bay will vary. The colourimetric analysis suggests that Fe^{3+} concentrations are likely to be highest in sediments transported early in the event and to decrease with land use change as proportionally more sediment is derived from alluvium.

3.6 *SOLUTES IN THE TULLY RIVER:*

3.6.1 Relationship between total dissolved solids and discharge:

The dissolved load of the Tully River was measured using the same general approach as that for suspended load. In 1987-88 103 conductivity determinations were made on Tully River water samples with a range of 30.6 - 47.6 uS.cm^{-1} ($\bar{x}$ = 38.9 $\pm$ 3.48) and in March-April, 1990 a further 33 determinations ranged from 18.4 to 38.2 uS.cm^{-1} ($\bar{x}$ = 30.6 $\pm$ 5.78). By applying the calibration relationship (Eqn. 3.4.3) to these results, a range of TDS for all samples from 15.6 to 38.2 mg.l^{-1} is estimated. Walling and Webb (1986) present a histogram showing the frequency of discharge-weighted mean solute concentration for a global sample of 496 rivers. The minimum concentration category is 0 to 50 mg.l-1 (in which < 20 % of the sample occurs), a concentration which was never exceeded in the Tully River. Thus the Tully carries solutes at very low concentrations on a global scale. However, Walling and Webb (1986) also show that the discharge-weighted solute concentration declines with increasing mean annual runoff, a pattern also observed for specific ions by Holland (1978) for streams in the U.S.A.. The Tully River TDS concentrations are comparable with the global discharge-weighted pattern as proposed by Walling and Webb (1986).

During the 1987-88 sampling period (Fig. 3.6.1) TDS observations ranged from 25.0 to 38.1 mg.l^{-1} ($\bar{x}$ = 31.5 $\pm$ 2.7; n = 103). The mean solute concentration during the period of baseflow prior to 4.2.1988 was 30.5 $\pm$ 2.0 mg.l^{-1} (n = 64), surprisingly similar to the overall mean and variability, including the relatively high discharge period during late February and early March. During this baseflow period there is an increase in TDS corresponding to a slight decrease in Q over the same period. Coincident with the hydrograph peaks are marked suppressions of the solute concentration, consistent with dilution of baseflow and throughflow waters with low residence time quickflow. There is no lag between TDS minima and Q maxima. An unexpected characteristic of these data is the peak in solute concentration which occurs during the falling stage after the 380 cumec hydrograph peak, at discharges well above baseflow. Subsequent to this TDS peak, the solute concentration declines to levels more consistent with those expected for the discharge.

The pattern of TDS in relation to discharge during the 1990 sampling period (Fig. 3.6.2) is similar to both the SSC and 1987-88 TDS data, in that TDS is highly responsive to changes in Q. Observations of stream conductivity (converted to TDS using Eqn. 3.4.3) were made on 33 occasions during March - April, 1990, with a mean of 25.1 ± 4.48 $mg.l^{-1}$ which is about 56 % of the mean SSC. The lowest value (15.6 $mg.l^{-1}$) occurred at the time of peak discharge and the maximum was 30.9 $mg.l^{-1}$, recorded during flood recession (Q = 75 cumecs). TDS was much less variable than SSC, the coefficient of variation being only 17.9 % compared with 71.6 % for SSC.

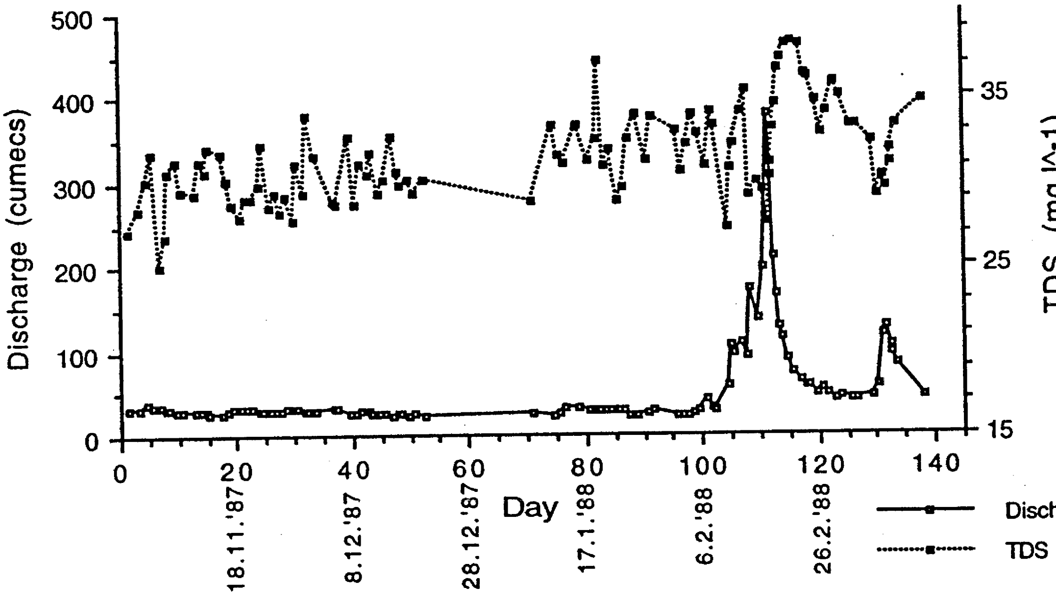


Fig. 3.6.1
Time series of discharge and TDS during the 1987-88 sampling period; n = 103.

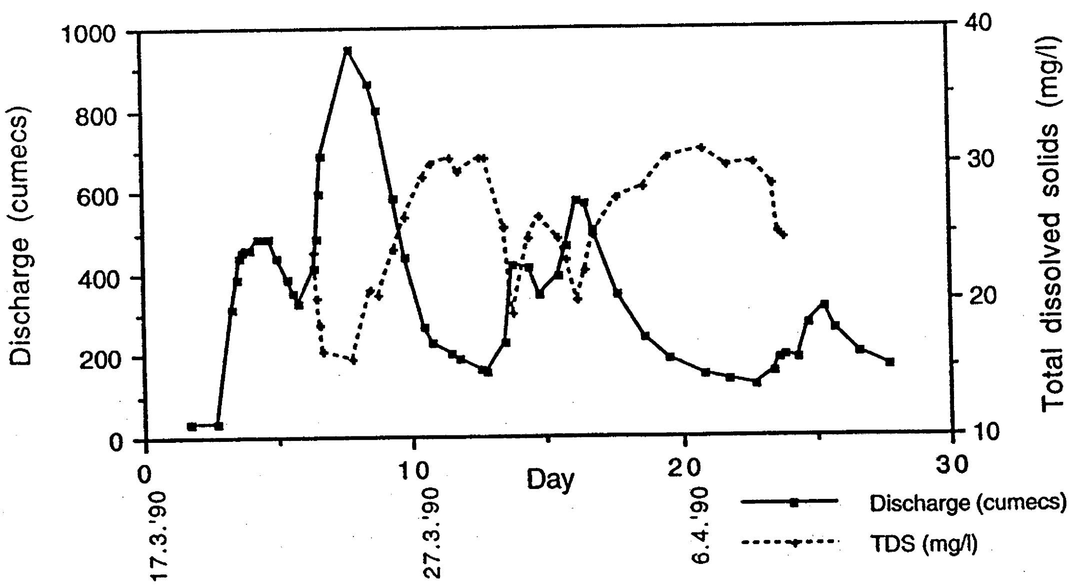


Fig. 3.6.2
Time series of discharge and total dissolved solids concentration (Tully River) during the March - April, 1990 wet season.

An interesting feature of these data is the TDS maxima which occur after the discharge peaks of 24.3.1990 and 2.4.1990, but before the discharge minima which occurred on the 29.3 and 8.4.1990, respectively. These peaks in solute concentration occur on the 28.3.1990 and 6.4.1990 at discharges of 205 and 150 cumecs, 33 and 20 % greater than the subsequent minimum discharges. This characteristic of the solute / discharge relationship is similar to that observed after the major runoff event of 1987-88. This pattern is evident in the results of Toler (1965) who interpreted it as a result of the high hydraulic conductivity in limestone terrain allowing rapid movement of groundwater to the stream (In Toler's study this occurred on a scale of months, rather than days in the Tully). In the case of the Tully River, it seems more likely that solute concentrations peak as solute laden soil water is discharged directly to stream channels as stage decreases.

The scatter plot depicting all observations of the relationship between Q and TDS is shown in Fig. 3.6.3. There is a strong, significant relationship between these variables:

$$ln\ TDS = 1.8893 + 0.77055\ .\ ln\ Q - 0.092329\ .\ ln\ Q^2 \qquad \text{[Eqn. 3.6.1]}$$
$$(n = 136;\ R^2 = 0.70)$$

Solute concentration declines as discharge increases, in keeping with the pattern of dilution by quickflow during runoff events. The point of inflection implied by this relationship suggests that the maximum solute concentration occurs at about 65 cumecs.

To facilitate comparison with reported results a model of the form TDS = a.Q^b was fitted to the data with the following result:

$$TDS = 43.4756\ Q^{-0.0911} \qquad (n = 136;\ R^2 = 0.40) \quad \text{[Eqn. 3.6.2]}$$

Comparison of the variance explained by this equation with that for the quadratic function above shows that it is a relatively poor fit. Walling and Webb (1983) reviewed global data for 370 stations and found that the mean of the exponent for this model was -0.17 and the modal class was -0.15 to -0.10. Thus the Tully River model above is fairly typical of those reported. The results show that, although the absolute solute concentrations in the Tully are low by world standards, the relative change in solute concentrations in response to stream flow variation is close to typical.

Rising and falling stage rating curves (Fig. 3.6.4) show that discharge and TDS are more closely related on rising stages, at which times the solute concentrations are relatively low. The minor inflection point evident in Fig.

3.6.3 is seen to occur during falling stage observations and is less evident during rising stages. Rating relationships for the solute load take the following forms:

ln TDS = 2.404 + 0.540. ln Q - 0.703.ln Q^2 [Eqn. 3.6.3]
(rising stage; n = 56; R^2 = 0.81)

ln TDS = 1.922 + 0.749. ln Q - 0.088.ln Q^2 [Eqn. 3.6.4]
(falling stage; n = 80; R^2 = 0.62)

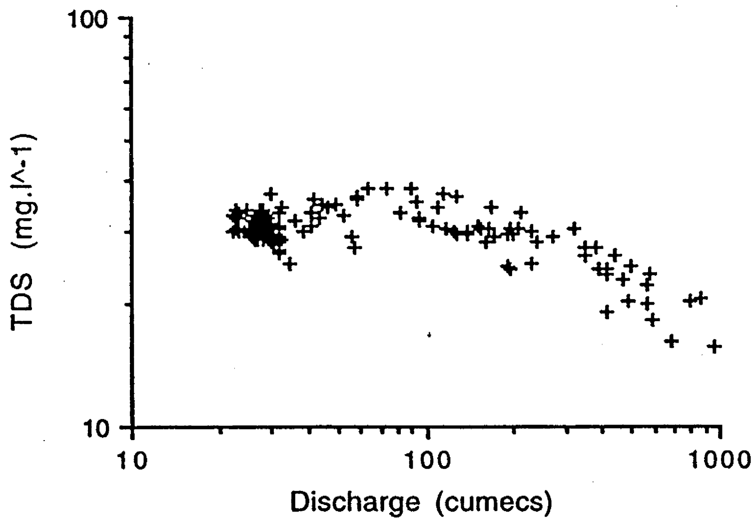


Fig. 3.6.3
Scatter plot showing the relationship between Q and TDS for samples from the Tully River; n = 136.

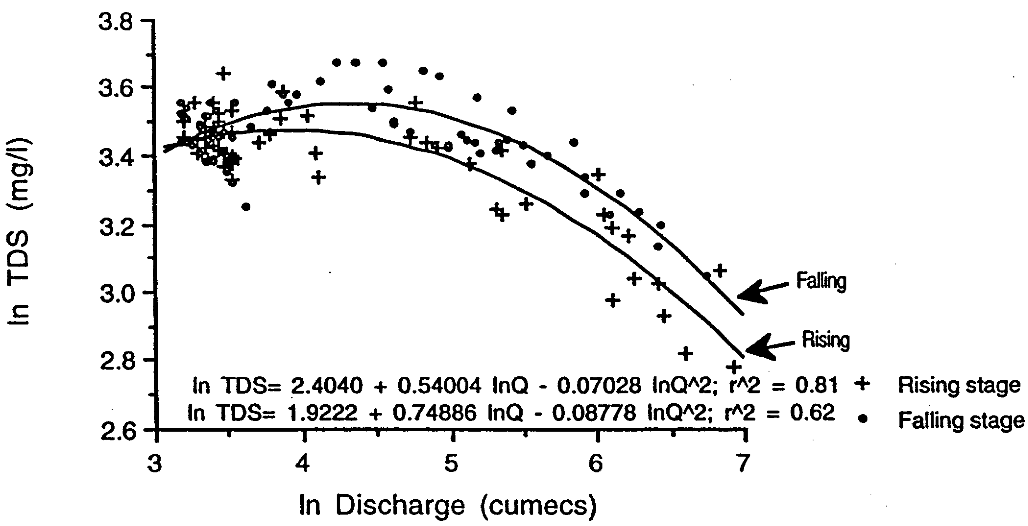


Fig. 3.6.4
Relationship between discharge and solute concentration in the Tully River for rising stage and falling stage observations.

Disaggregation of the 1987-88 and 1990 data sets revealed no significant difference in the relationships between TDS and Q between the two sampling periods.

The pattern of hysteresis in the Tully River TDS concentrations (1990 sampling period) is illustrated in Fig. 3.6.5. Over four flood peaks, the Tully River exhibits concentrations varying by a factor of 2, anti-clockwise hysteresis and no evidence of depletion of solutes over time. This is in marked contrast to that reported for German's Creek on the coast of New South Wales (Cornish, 1982), for example, where solute concentrations vary by a factor of 5, are hysteretic clockwise and are strongly depleted over time in the course of four events.

Hysteresis may be induced by the initial flushing response (discussed above), by solute depletion during the event, by the kinematic differential inducing a lag between discharge maximum and solute minimum (clockwise hysteresis) or by floodplain storage delaying the flood peak, and soil water discharge to the stream during the falling stage (anti-clockwise hysteresis). There is no evidence to suggest that any of the clockwise hysteresis inducing factors occur in the Tully catchment. On the other hand, significant floodplain storage is known to occur in the Tully catchment. An additional factor which could contribute to the anti-clockwise pattern is the inflow to the Tully of relatively high TDS Murray River waters during the Tully River recession curve.

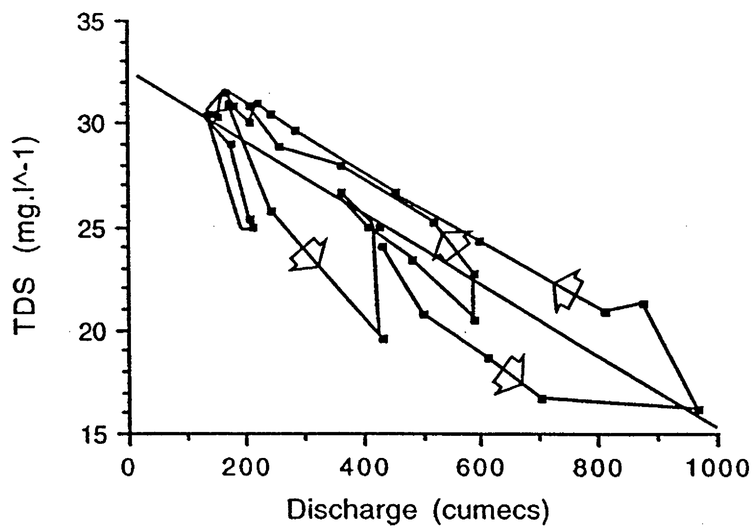


Fig. 3.6.5
Hysteresis in the relationship between discharge and conductivity in the Tully River during March-April, 1990; n = 33.

3.6.2 Solute chemistry of Tully River waters:

The concentrations of the selected components of the solute load monitored during the 1990 sampling period are shown in Table 3.6.1. For all determinations both P (as PO_4) and Sr concentrations were below the minimum detectable limits of the analytical method (c. 0.02 and 0.004 $mg.l^{-1}$, respectively). (Note: Mean Tully River phosphate concentrations are about 50 % of the concentration of particulate P (Mitchell, *et al.*, 1991); Particulate P concentrations are greatest at times of highest sediment concentration, and are therefore associated with high stream flows.)

The two dominant ions are Na^+ and Cl^- which, on average, represent about 60 % of the ten ions analysed. The relative importance of Na^+ and Cl^- may be a result of atmospheric accession to the coastal catchment. However, all samples analysed have very low solute concentrations. Si, the third ranked in concentration, is also the most variable. The coefficient of variation is reasonably consistent for all other solutes (22 - 33 %) with the exception of Total N (44 %), which is present only at very low concentrations, and Si for which the coefficient of variation is 69 %. All solute concentrations in the Tully River are considerably lower than the global average estimates, with the exception of nitrogen which is about 50 % higher.

Solute component	n	mean ($mg.l^{-1}$)	std. dev.	minimum	maximum	coefficient of variation
Cl^-	37	4.30 (7.8)	1.32	0.58	8.37	30.8
Na^+	37	3.10 (6.3)	1.01	0.51	5.45	32.6
Si	37	1.55 (6.5)	1.07	0.01	3.99	68.7
K^+	37	1.10 (2.3)	0.24	0.19	1.43	22.1
SO_4	37	1.00 (3.7)	0.28	0.13	1.72	27.8
Ca^+	37	0.91 (15)	0.26	0.20	1.33	28.3
Mg^+	37	0.54 (4.1)	0.15	0.16	0.87	27.1
Total N	37	0.36 (0.23)	0.16	0.10	0.95	44.1

Table 3.6.1
Summary statistics of eight components of Tully River solute load, March - April, 1990. Values in brackets following mean concentrations are global river water average estimates (Livingstone, 1963).

Fig. 3.6.6 shows the relationship between the major cation chemistry of the Tully River and that of streams elsewhere in Australia and globally. Not surprisingly, these results place the Tully clearly in the region of precipitation-dominated stream waters with high Na:Ca ratios. This is attributed to the very high rainfall and close proximity to the coast, with predominantly onshore winds. The Tully is consistent with the results for North Babinda Creek (Douglas, 1968) which is an area of similar rainfall and proximity to the coast. The north Queensland results plot closely to the headwaters, in the Australian Alps, of the Murray River, NSW, but with slightly higher relative Na concentrations. A slight modification of Gibbs' (1970) and Cornish's (1987) figure is proposed (Fig. 3.6.6 (b)) to account for declining Na:Ca ratios and solute concentrations in precipitation with distance from the coast (Hutton and Leslie, 1958; Brasell and Gilmour, 1980; Walker *et al.*, 1981).

The relationships between discharge and selected components of the solute load are shown in Fig. 3.6.7. Five components of the solute load (Cl, Na, Si, Ca, Mg) are significantly, inversely correlated with discharge. Those solutes not correlated with discharge are not necessarily independent of it. Total N, for example, exhibits a great deal of variability in concentration at low discharges, but converges on the mean concentration at high flows. SO_4, on the other hand, has greatest variability at higher flows.

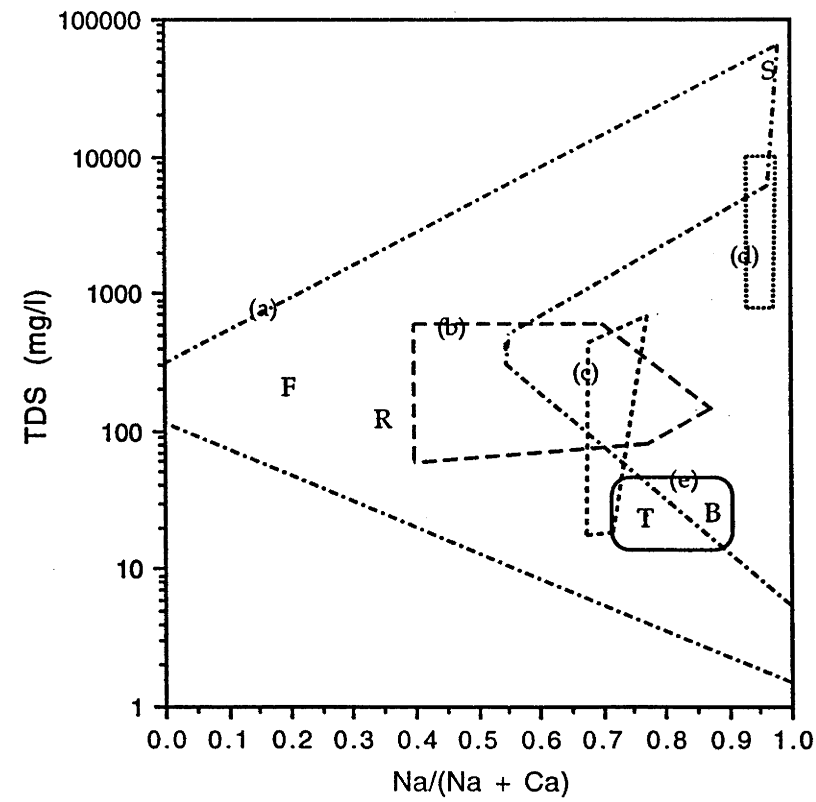


Fig. 3.6.6 (a)

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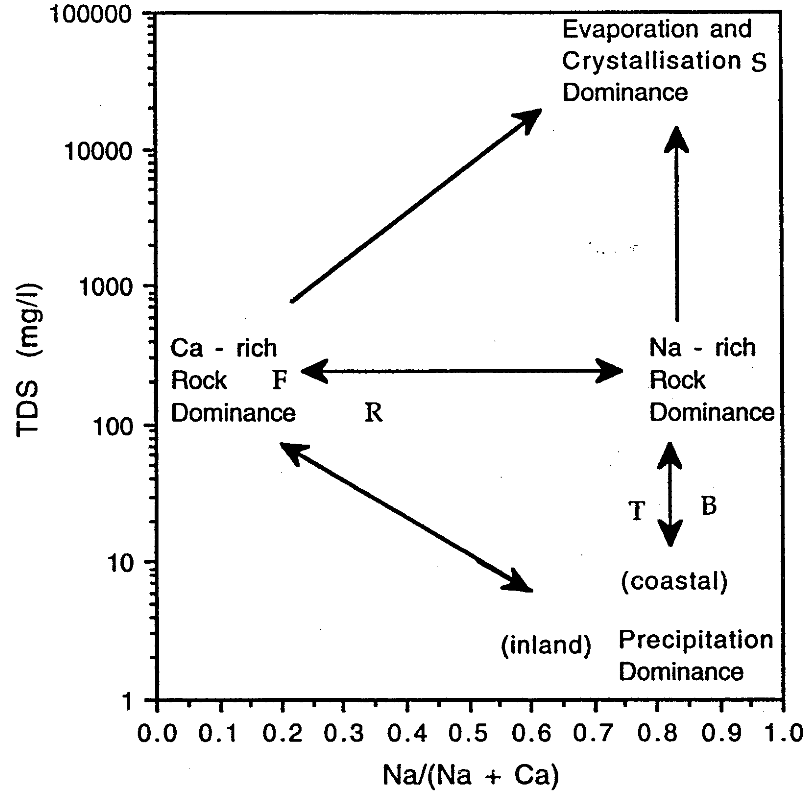


Fig. 3.6.6 (b)
Relationship of Tully River solute chemistry to streams elsewhere in Australia and the world (a) and in relation to the major controlling factors (based on Gibbs, 1970; Cornish, 1987); Legend: S seawater (Gibbs, 1970), F - World average freshwater (Conway, 1942), R - world average river water (Meybeck, 1983), B - North Babinda Creek (Douglas, 1968), T - Tully River (this study); (a) - world's surface waters, (b) - southeast Australian streams, (c) - Murray River, NSW (long profile), (d) - southwest Western Australian streams, (e) - northeast Queensland streams.

Inter-relationships between the various components of the river load are shown in Table 3.6.2, which shows that SSC is inversely related to TDS, Si, Cl, Mg, Ca and Na. TDS on the other hand is positively correlated with Si, Cl, Mg, Ca and Na. The latter four ions are all strongly ($r \geq 0.85$), mutually correlated. Potassium is significantly correlated with these ions but the relationship is not as strong. Total N concentrations are significantly correlated with SO_4 and with K. SO_4 also exhibits a positive correlation with K and Cl. Potassium is also correlated with Cl, Mg, Ca and Na.

There are four main patterns exhibited in the interrelationships between stream load components and discharge:-

i. SSC increases with discharge, and is inversely related to TDS.

ii. Solutes largely derived from atmospheric accession and weathering, and dominated by Cl, Mg, Ca and Na. These are inversely related to Q.

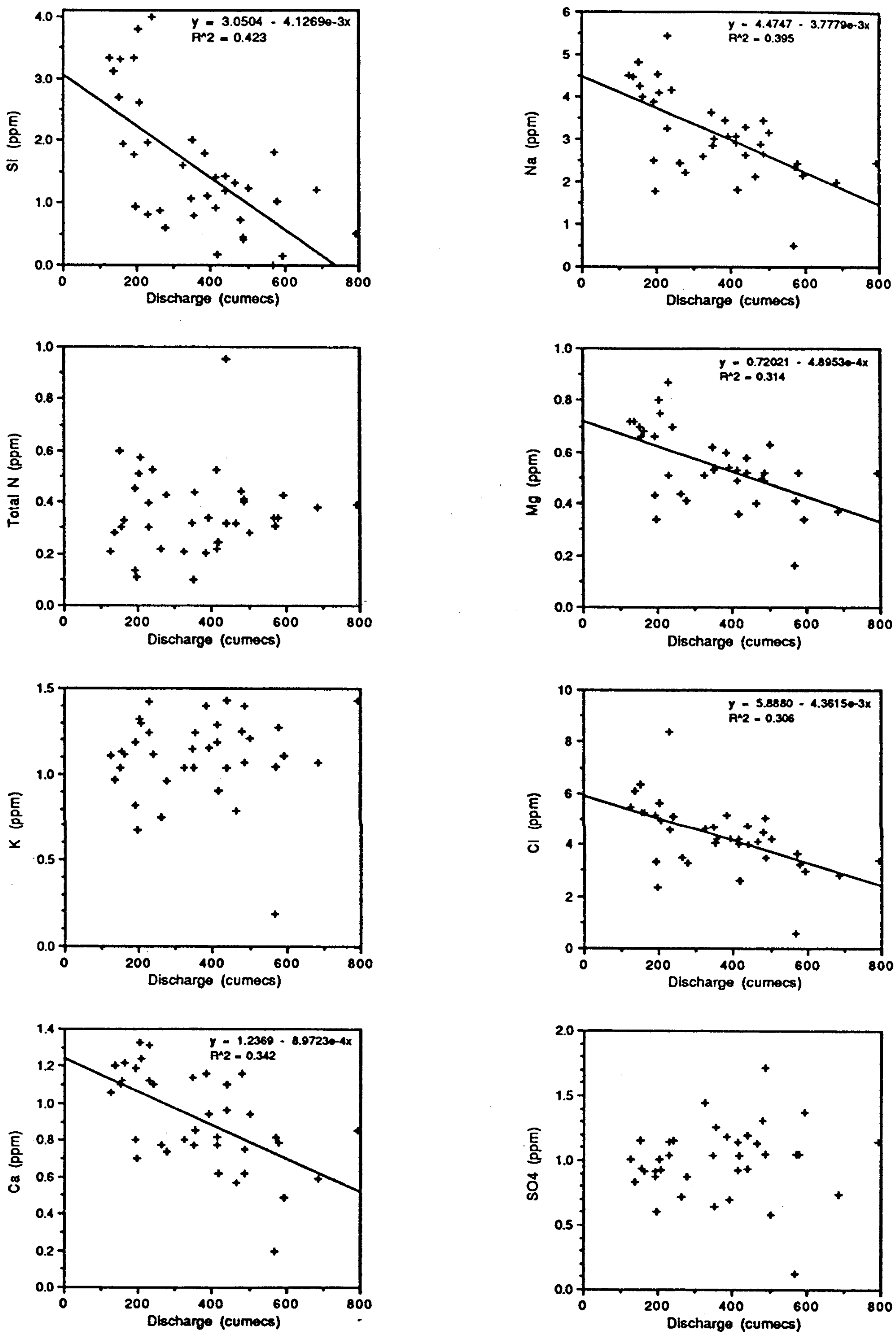


Fig. 3.6.7
Relationships between discharge and selected components of the solute load in the Tully River.

	Q	SSC	TDS	Tot N	Si	Cl	SO_4	Mg	Ca	K	Na
Q	1										
TDS	-.74**	-.80**	1								
Tot N	.00	-.03	.09	1							
Si	-.42*	-.61**	.75**	.09	1						
Cl	-.31*	-.53**	.75**	.21	.67**	1					
SO_4	.00	.03	.03	.41	.15	.44*	1				
Mg	-.31*	-.63**	.81**	.25	.72**	.93**	.35*	1			
Ca	-.34*	-.56**	.80**	.20	.66**	.86**	.33*	.92**	1		
K	.00	-.14	.19	.32	.20	.58**	.62**	.65**	.62**	1	
Na	-.40*	-.56**	.82**	.26	.75**	.96**	.40*	.97**	.90**	.59**	1

Table 3.6.2
Correlation matrix showing interrelationships between various components of the Tully River load during the 1990 sampling period ($n = 37$; $p < 0.05$ -*; $p < 0.005$ -**).

iii. Solute load derived largely from fertiliser inputs to the catchment, eg. Total N, and not related to Q.

iv. Solute load derived partly from fertiliser inputs and partly from geomorphic processes, such as SO_4 and K, and not related to Q.

3.7 SEDIMENT AND SOLUTE FLUX FROM THE TULLY RIVER:

The relative importance of solutes and particulates in the Tully River for the range of discharges observed is illustrated in Fig. 3.7.1. As expected, at low flows the solute concentrations are greater. As discharge increases the relative importance of suspended sediment increases until, at about 170 cumecs, it forms the majority of the load. During the period 1973 to 1986 this discharge is exceeded, on average, in 5.3 months of the year. When the river peaks the SSC peak has already passed and the solute concentration is at a minimum. At a recession discharge of about 370 cumecs solute concentrations once again exceed those of suspended sediment. This pattern is indicative of the overall interaction and will only rarely be the case for a given event.

Time series of sediment and solute loads for the 1990 sampling period are shown in Fig. 3.7.2. The much higher temporal variability of suspended load, by comparison with solute load, is evident.

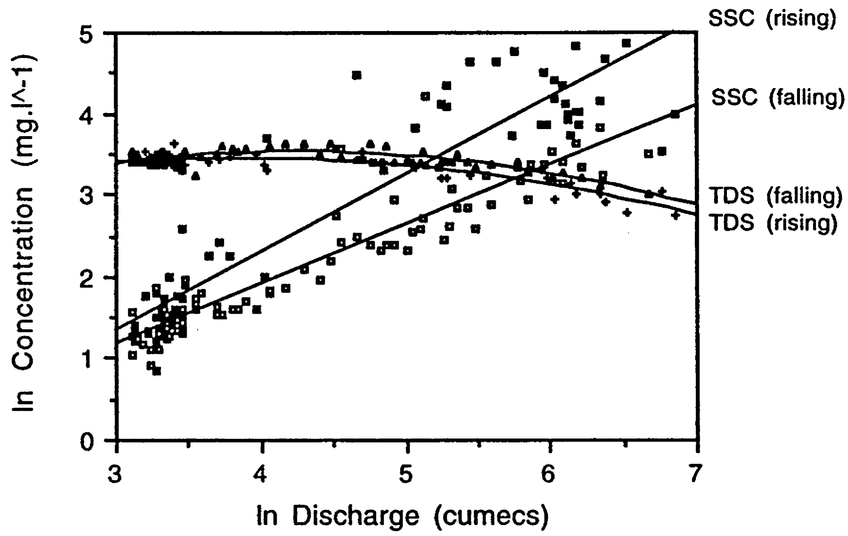


Fig. 3.7.1
The relative magnitude of SSC and TDS in the Tully River over the observed range of discharge for rising and falling stage.

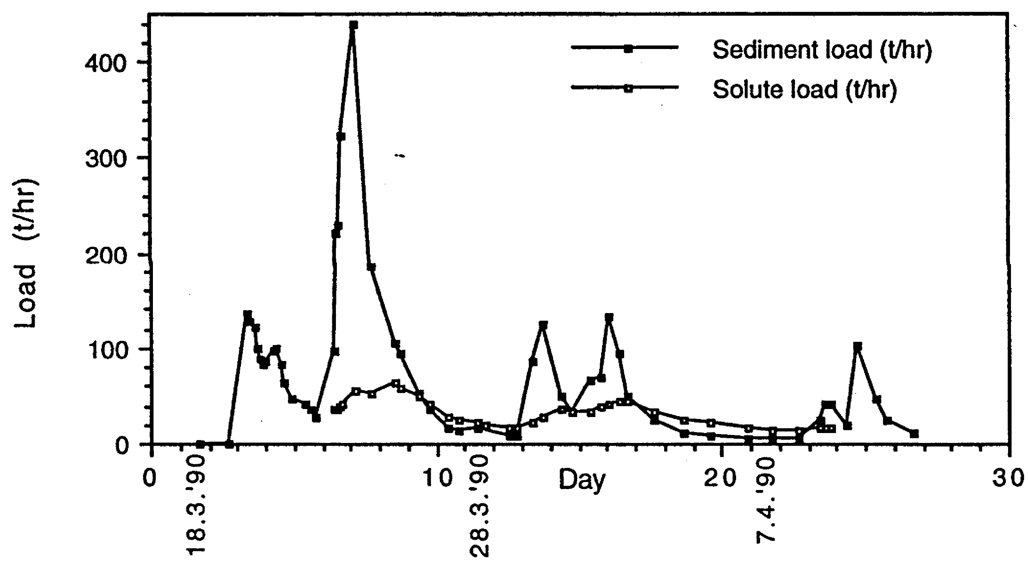


Fig. 3.7.2
Time series of suspended sediment and solute loads from the Tully River during the 1990 sampling period.

In the following paragraphs, suspended sediment, total solutes and nitrogen fluxes from the Tully River catchment for the 1990 water year are estimated using the rating relationships derived during the 1987-88 and 1990 sampling periods and the daily QWRC streamflow data. Fluxes for the year are contrasted with those for the wet season only, defined here as the period 20.3.1990 to 19.5.1990 (17 % of the year), during which 53 % of streamflow occurred.

Sediment yield for the Tully catchment for the 1990 water year was estimated using the sediment rating relationships for rising and falling stages (Eqn. 3.5.2 and 3.5.3) and the daily streamflow data for the Euramo gauging station. Corrections to the suspended sediment concentrations calculated from the rating relationship were made to account for bias due to the log transformation (Ferguson, 1986a, b; Koch and Smillie, 1986). As stated in Chapter 3.5.5.2, no correction is considered necessary for bias induced by surface sampling. Bedload is not included in this analysis, although Douglas (1973) suggested that bedload varied from 5 % (rock bed) to 20 % (sand bed) for streams in the region, and between 10 % (upper reaches) and 20 % (lower reaches) for regional streams on granite. The estimate is conservative because the sampling interval used, in relation to the skewed distribution of both the hydrograph and sedigraph, is more likely to truncate peaks in both Q and SSC than to truncate troughs.

The calculated sediment yield for the 1990 water year is 104 000 t, with daily sediment yields ranging from 3.3 t to 14 360 t ($\bar{x}$ =286 t.day^{-1}; Fig. 3.7.3). This is equivalent to a specific yield of 71 t.km^{-2}.yr^{-1}. About 80 % of the total suspended sediment discharge from the Tully River during 1990 occurred during the two month period defined as the wet season. The calculated yield is about an order of magnitude lower than the "natural" rate reported by Prove and Hicks (1991), but similar to the regional yield estimates of Douglas (1967a, c).

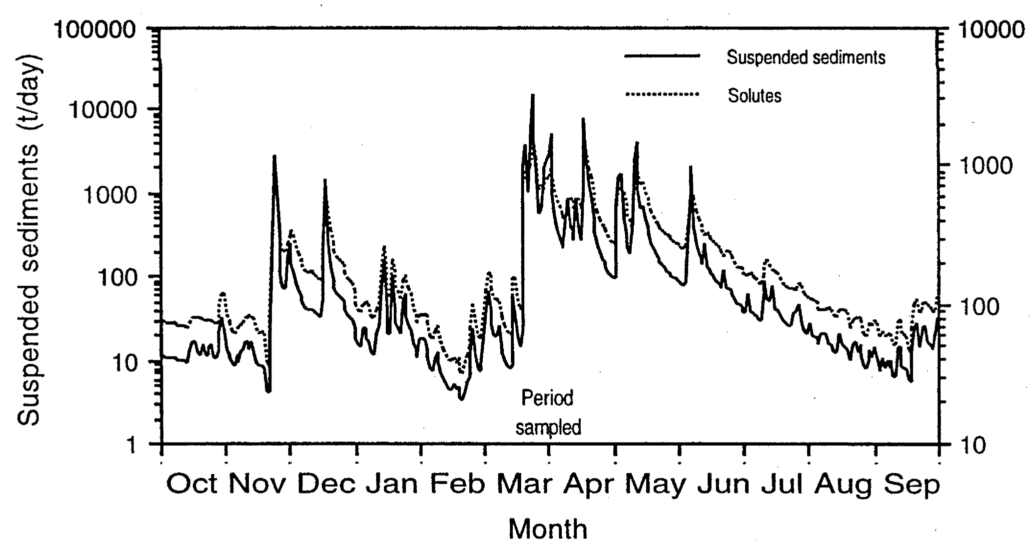


Fig. 3.7.3
Estimated daily suspended sediment and solute flux from the Tully River, 1990 water year.

The sediment yield calculated for 1990 is used as the reference point for the sediment yield time series derived in the following chapter.

Solute yield for the 1990 water year was also estimated using the rating relationships for rising and falling stages (Eqn. 3.6.3 and 3.6.4) and the daily streamflow data for the Euramo gauging station. In this case also, correction for log transformation-induced bias was necessary. The total solute yield for 1990 was 83 500 t, equivalent to 56 $t.km^{-2}.yr^{-1}$. Daily solute yields ranged from 31.9 t to 1 495 t ($\overline{x}$ = 228). About 47 % of total solute yield occurred during the defined wet season. These solute yields include precipitation inputs (Chapter 3.4.3) which are likely to be about half the solute yield.

Douglas (1964) emphasised the importance of the dissolved load as a major component of the total catchment denudation. However, he also pointed out (Douglas, 1967c) that, despite the frequent assertion that the humid tropical climate favours intense chemical weathering, streams in granitic catchments of the north Queensland wet tropics carry higher suspended sediment than solute loads. In the Tully River, solutes comprised about 44 % of the total river load in 1990, and this declined to about 32 % during the two month wet season period. Relatively low solute loads during this period are clearly due to the dilution effect of high precipitation inputs (Chapter 3.6), but are also likely to be affected by reduced solute concentrations in rainwater during periods of frequent and heavy rain (Chapter 3.4.3). By comparison with other streams in the region the suspended:dissolved load ratio seems reasonably typical. For example, for four northeast Queensland streams with annual rainfall > 2 000 (Douglas, 1973), the proportion of total load (exclusive of bedload) attributed to solutes ranged from 33 to 54 %. The suspended:dissolved load ratio is consistent with Douglas' (1973) suggestion that, for streams in eastern Australia, the suspended sediment contribution exceeds that of solutes in catchments with high runoff (> 1 500 $mm.yr^{-1}$).

The total load from the Tully River (1990 only; exclusive of bedload) is c. 127 $t.km^{-2}.yr^{-1}$. Assuming a rock density of 2.6 (rock density, rather than soil density, is used for purposes of comparison with Douglas' (1973) data for the region) a denudation rate of 50 $m^3.km^{-2}.yr^{-1}$ is likely from the Tully (possibly c. 38 $m^3.km^{-2}.yr^{-1}$ if estimated precipitation inputs are taken into account). This is slightly higher than the mean denudation rate (exclusive of bedload) for eleven streams in the region (39 $\pm$ 69 $m^3.km^{-2}.yr^{-1}$) but lower than the mean of four regional streams with rainfall > 2 000 mm (77 $\pm$ 113 $m^3.km^{-2}.yr^{-1}$; Douglas, 1973). It is concluded that the Tully River is reasonably typical of granitic catchments in the wet tropics region in terms of both the denudation rate and the suspended:dissolved load ratio.

Evaluation of the Tully River results in the context of reported spatial variation in world denudation rates is difficult because of the substantial discrepancies between the magnitude of rates reported in these compilations, and between the spatial patterns of those rates (Selby, 1982).

Wilson (1973) points out that the literature includes relationships between sediment yield and climate which predict sediment yield maxima under a wide variety of climatic conditions including:- semi-arid or arid conditions (Langbein and Schumm, 1958; Fournier, 1949), subhumid conditions (Rango, 1970; Wilson, 1973), tropical conditions (Fournier, 1949; 1960; Strakhov, 1967; Wilson, 1973) and cold climates (Corbel, 1964). Estimates for regions which include the north Queensland wet tropics include:-
Fournier (1960) _ _ _ _ _ _ _ _ _ _ _ _ _ _1 000 - 2 000 $t.km^{-2}.yr^{-1}$.
Strakhov (1967; in Selby, 1982: 229) _ _ _ _ 50 - 100 $t.km^{-2}.yr^{-1}$.
Judson and Ritter (1974; Class A climate) _ _$\bar{x}$ = 71.5 $t.km^{-2}.yr^{-1}$.

The absence of young mountain ranges and active volcanos in the tectonically quiescent, low relief Australian landscape results in slow sediment supply by comparison with the more active regions of North America and Europe (Bowler, 1986). Fournier's (1960) data set is based largely on streams from these less stable areas and assumes Australia to be more tectonically active than is the case. Consequently, estimated sediment yields are about an order of magnitude too high, about what would be expected in contrasting tectonically active and stable catchments. The Tully catchment data is consistent with the estimates of Strakhov (1967) and Judson and Ritter (1974). Langbein and Schumm's (1958) compilation includes no catchment with rainfall > 1 300 mm, and is therefore not applicable to the north Queensland wet tropics. Douglas' (1973) curve, based on eastern Australian data and supported by the results of Neil and Fogarty (1991) and this study, indicates that sediment yields increase as the runoff increases.

Nitrogen flux:

Nitrogen is an ecologically important nutrient in GBR waters (Furnas, 1988), concentrations of which are strongly influenced by fluvial inputs. Temporal variation in nitrogen load from the Tully River is largely controlled by variation in discharge rather than variation in nitrogen concentrations (Fig. 3.6.7). The maximum nitrogen discharge rate during the 1990 sampling period was 1.5 $t.hr^{-1}$ and the mean daily nitrogen flux for the period was 5.7 $t.day^{-1}$ (area under curve; Fig. 3.7.4). This refers only to dissolved nitrogen. By comparison, Mitchell *et al.* (1991) report fluxes of 0.36, 2.21 and 1.84 $t.day^{-1}$ for the South Johnstone, Herbert and Tully Rivers, respectively. Their data refer to dissolved inorganic nitrogen (DIN) and do not include dissolved organic nitrogen (DON).

Mitchell *et al.* (1991) also present particulate-N (PN-N) and Total-N data for the South Johnstone and Herbert Rivers, with PN:DIN ratios of 3.13:1 and

3.19:1, respectively. Assuming this ratio for the Tully River, a total N flux of c. 5.83 t.day^{-1} can be estimated for the Tully from Mitchell *et al.*'s data. By contrast, assuming a PN:DIN ratio of 3.16 and that DIN=DON (Mitchell *et al.*, 1991), a 1990 sampling period flux of c. 9 t.day^{-1} is estimated from Fig. 3.7.3. Clearly, the N-flux is highly dependent on streamflow and periods of high streamflow are likely to result in the coincidence of peak N-fluxes and river plume movement into the vicinity of island fringing reefs. For example, the peak 5 day N-flux from the Tully River to Rockingham Bay during the 1990 sampling period is estimated (from Fig. 3.7.4) at 110 t.

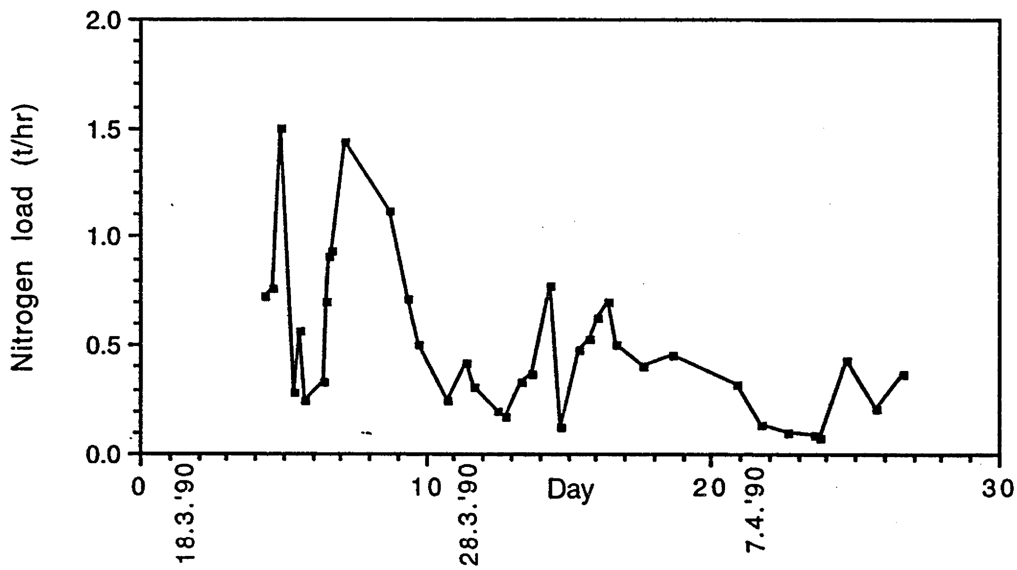


Fig. 3.7.4
Time series of dissolved nitrogen load in the Tully River during the 1990 sampling period.

Although N concentrations are not related to discharge (Fig. 3.6.8), those on rising stages are correlated (DN-N = 0.1104 + 4.623.10^{-3} .Q; R^2 = 0.406; n = 12). Using this relationship for rising stages and the mean N concentration for falling stages (0.359 $\pm$ 0.158 mg.l^{-1}) and the daily discharge data, the DN-N flux for the 1990 water year is estimated at 943 t (2.6 t.dy^{-1}). Of this 533 t (57 %) was discharged during the 17 % of the year in the wet season period (Fig. 3.7.5). Based on the above assumptions [DIN = DON; PN = 3.6.DIN], the total N flux for the year is estimated at 1 700 t.

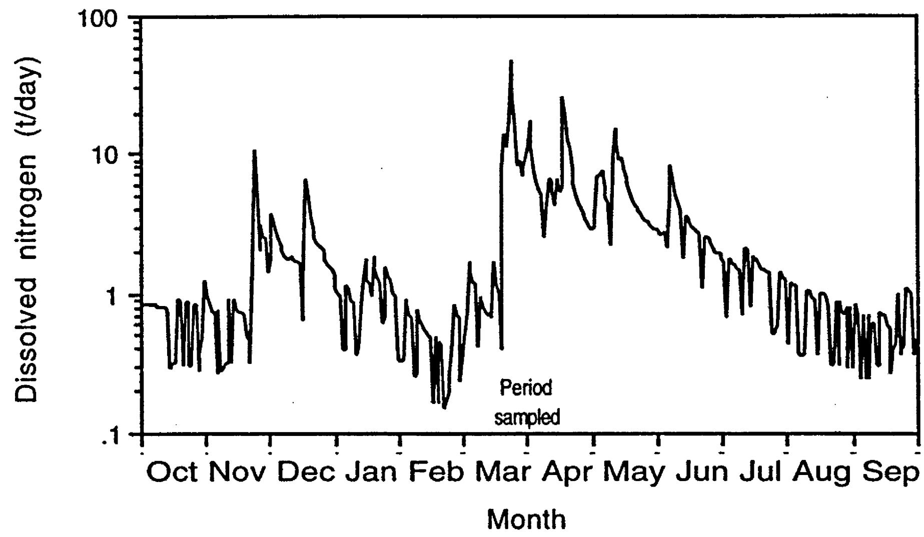


Fig 3.7.5
Time series of dissolved nitrogen load during the 1990 water year.

3.8 COMPARISON OF TULLY RIVER AND MURRAY RIVER STREAMFLOW AND SUSPENDED SEDIMENT CONCENTRATION CHARACTERISTICS:

As pointed out in Chapter 2.1.3, the morphology of the lower Murray catchment differs from that of the lower Tully, with more frequent overbank flows, greater channel sinuosity, greater channel constriction by living vegetation and debris, and greater overbank storage in abandoned stream channels.

Fig. 3.8.1 shows variation in stage for the Tully and Murray Rivers during the March - April, 1990 sampling period. Comparison of the curves for the two streams shows that the Tully River at Euramo has a much more responsive hydrograph than the Murray at the highway bridge, in spite of having a catchment area about three times that of the Murray. Furthermore, streamflow in the Tully River returns relatively rapidly to close to its pre-flood level. Streamflow in the Murray, on the other hand, is maintained at a level closer to its flood maximum than to the pre-flood flow. During the flood flows in the Tully River on 24.3.1990 and 25.3.1990, the Murray was inaccessible. However, the peak stages recorded in the Murray are very close to bankful, and it is unlikely that the actual peak was very much greater than that observed.

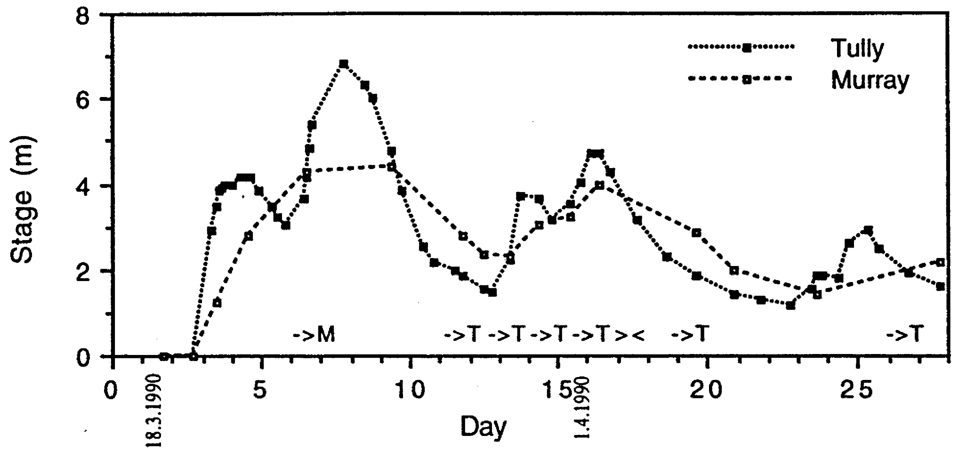


Fig. 3.8.1
Stage in the Tully and Murray Rivers from 18.3.1990 to 13.4.1990. (Datum is baseflow prior to onset of the wet season; -> M = time of flow from the Tully to the Murray along Weiss Creek; -> T = time of flow from the Murray to the Tully; > < = time of high stage in Weiss Creek, but no flow).

Prior to the commencement of rainfall, the SSC in the Murray (7.8 and 7.0 $mg.l^{-1}$) was marginally higher than in the Tully (5.3 and 5.7 $mg.l^{-1}$). Throughout the remainder of the sampling period, SSC in the Tully was much more variable than in the Murray, with much higher peaks and falling to slightly lower concentrations between events (Fig. 3.8.2). Factors contributing to the lower SSCs recorded in the Murray include a smaller proportion of montane terrain, a smaller proportion of agricultural land, and lower stream velocities than in the Tully. Maintenance of relatively high SSC at low flows is attributed to flushing of organic detritus from floodplain swamps, as suggested for catchments of similar morphology in the lower Tully catchment (Chapter 3.10).

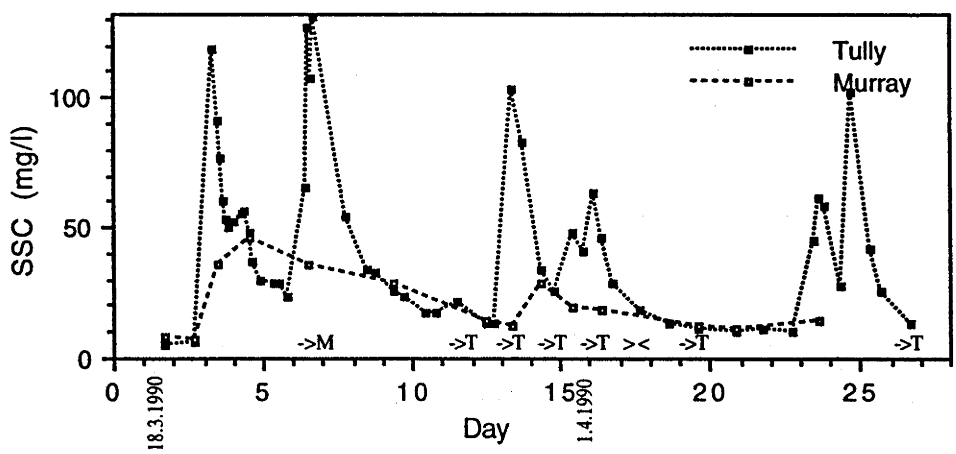


Fig. 3.8.2
Suspended sediment concentration in the Tully and Murray Rivers from 18.3.1990 to 13.4.1990. (Flow directions as for Fig. 3.8.1).

During the 1990 sampling period the mean SSC for 14 observations on the Murray River was 20.9 $mg.l^{-1}$ (s.d. = 12.09; range = 7.0 - 46.1) compared with a Tully River mean of 45.0 $mg.l^{-1}$ (s.d. = 38.66; range = 5.3 - 126.9). SSC in the Tully was significantly greater (paired t-test; $p \leq 0.01$). Fifteen paired observations during the 1987 - 1988 sampling period were not significantly different. This is attributed to the much lower flows during this period in which the Murray River mean was 15.0 $mg.l^{-1}$ (s.d. = 11.44; range = 4.9 - 37.3) compared with a Tully River mean of 16.9 $mg.l^{-1}$ (s.d. = 23.61; range = 2.5 - 76.2). Peak SSCs in the Tully were again much higher than in the Murray during this period.

During the major flood in the Tully River on 24.3.1990 and 25.3.1990, the Tully flowed strongly into the Murray via Weiss Creek. With the more rapid hydrograph recession in the Tully, the flow was reversed and for the remainder of the sampling period was from the Murray to the Tully. Flow velocities from the Murray to the Tully were always low by comparison with the high velocity Tully -> Murray flow. A minor perturbation of this pattern occurred when flow in Weiss Creek ceased on 3.4.1990 due to a rise in the Tully (Fig. 3.8.1). SSC in Weiss Creek was not monitored. However, there is no indication that the influx of high-turbidity Tully River water significantly affected SSC in the Murray (Fig. 3.8.2).

Although Hausler (1991) estimated that Murray River runoff is 65 % of that from the Tully, it is clear that flood discharges in the Murray are strongly damped by the particular characteristics of the Murray flood plain and channel. As a result, flood peaks are unlikely to be sufficiently large to generate a sediment plume capable of propagating across Rockingham Bay. Furthermore, suspended sediment concentrations in the Murray are significantly lower than in the Tully, a difference which increases at flood discharges. These results suggest that the Murray River will have a relatively minor impact on suspended sediment concentrations in Rockingham Bay, by comparison with the Tully River. Murray River waters which merge with the Tully plume may increase its spatial extent slightly, but will probably also result in some dilution of the SSC in the plume.

3.9 LONG PROFILE VARIATION IN SUSPENDED AND DISSOLVED LOADS IN THE TULLY RIVER.

The locations of long profile water quality sampling points along the Tully River are shown in Fig. 3.9.1. Site 4 is just below the power station outlet pipe, which is the main water source at low flows. Site 3 is near the lower end of the upper gorge reach, and Site 2 samples the lower gorge reach. Site 1 samples the upper alluvial reach and most of the lower alluvial reach.

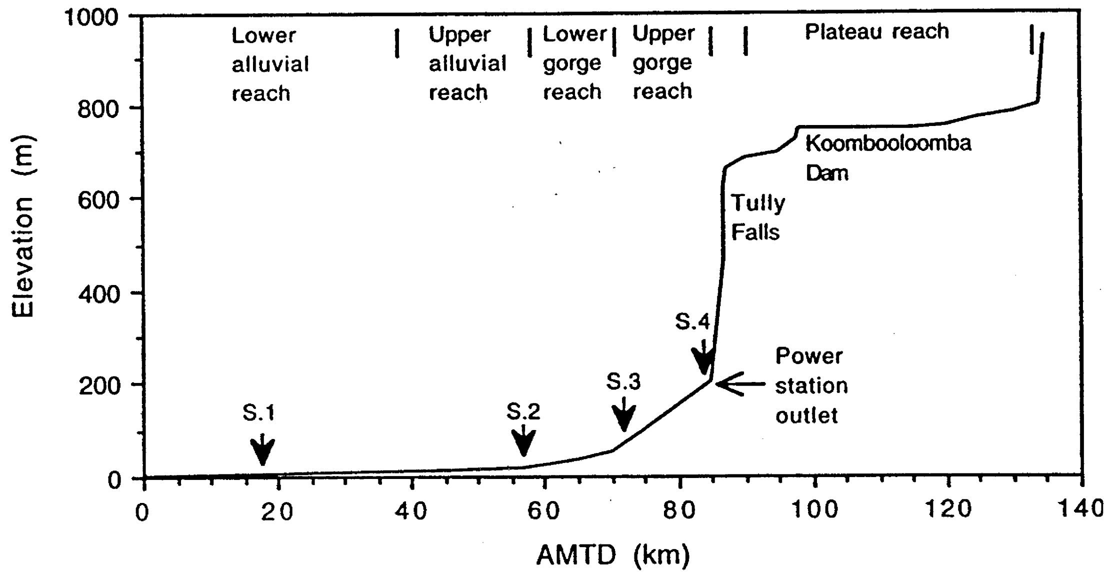


Fig. 3.9.1
Location of sampling sites along the Tully River in relation to stream channel morphology.

The trends in SSC and TDS with distance downstream are illustrated in Figs. 3.9.2 and 3.9.3 for sampling stations on the Tully River (Sites 1-4). A quite consistent pattern of increased concentrations for both parameters is observed with distance downstream.

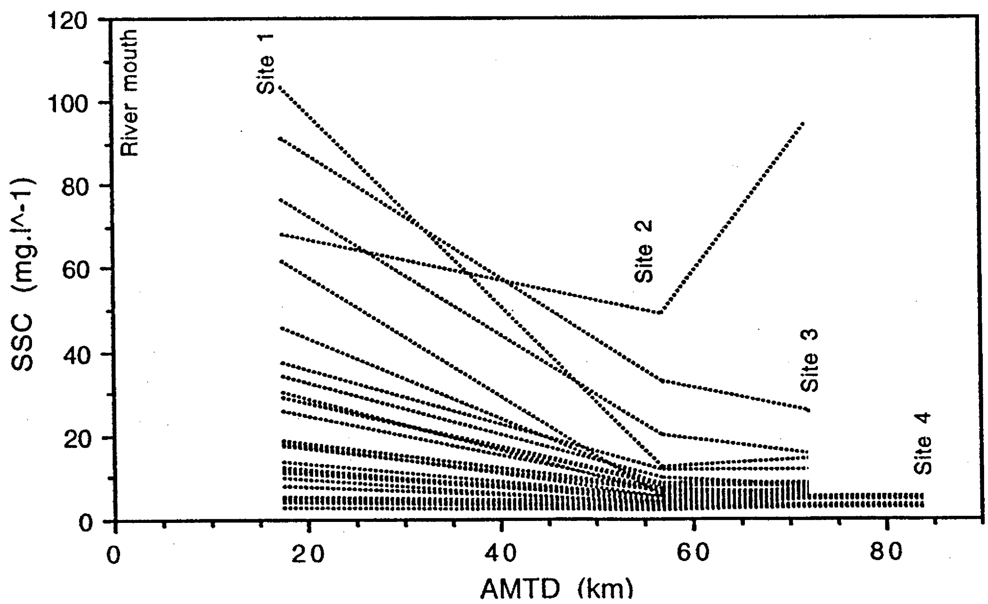


Fig. 3.9.2
Long profile variation in SSC in the Tully River from AMTD 17.5 to 84 km (29 observations).

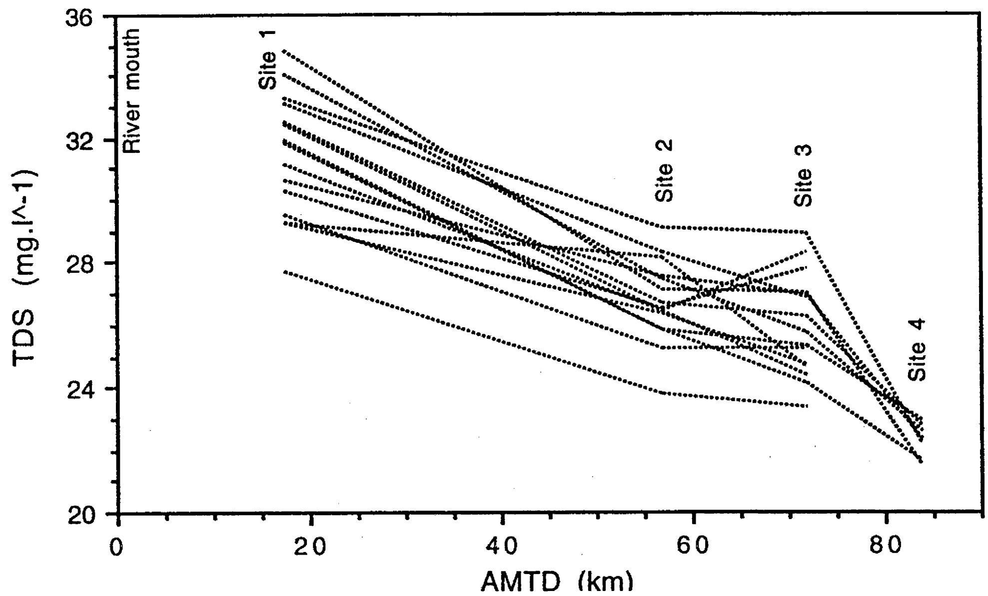


Fig. 3.9.3
Long profile variation in TDS in the Tully River from AMTD 17.5 to 84 km (15 observations).

In the case of TDS (Fig. 3.9.3) there is a generally monotonic increase downstream, increasing most sharply from Site 4 to Site 3. SSC is similar, but with a marked increase between Site 2 and Site 1 (Fig. 3.9.2). With the exception of roadworks associated with the Kareeya powerstation and some logging roads, generally upstream of Koombooloomba Dam and a small area of improved pasture, there is little disturbance of the catchment upstream of Site 2. It appears most likely that the slightly elevated suspended and dissolved concentrations at Site 3 may be attributed to slope failure in cuttings associated with the powerstation access road and that the increase between Site 2 and Site 1 is a result of such factors as land use change (cropping and accelerated stream bank erosion) and flushing of particulates and solutes out of swamps in low lying areas of the floodplain during runoff events. Lower solute levels upstream is also likely to be a consequence of lower atmospheric accession to inland parts of the catchment (Chapter 3.4.3).

The high variability of both TDS and SSC observations, particularly at Site 1 (Figs. 3.9.2 and 3.9.3) is in part a consequence of variation in Q, with which TDS and SSC are significantly correlated. (Chapter 3.5 and 3.6).

A paired 't-test' indicates that both the SSC and TDS are significantly ($p \leq 0.05$) greater at Site 1 than at Site 2.

The pattern of long profile SSC variation evident in the Tully river is the reverse of that reported by Richey *et al.* (1986) for the Amazon. In that case, the maximum SSC occurred at the station furthest upstream (c. 2 500 km, in the Andes foothills) with a decline downstream. Sediment concentrations observed were generally higher than those in the Tully. On the other hand, Douglas (1967b) reports higher (about double) suspended sediment loads in the lower reaches than the upper reaches of the Barron River, and Davies and Millstream Creeks, north Queensland. This he attributes to land use change in the lower reaches, a pattern consistent with that in the Tully River. Similar patterns have been reported elsewhere in eastern Australia (eg. Loughran *et al.*, 1986). It is likely that long profile suspended sediment concentrations will decline downstream under natural conditions and the reverse may occur when land use intensification occurs on the floodplain.

Catchment lithology is generally seen as the major determinant of streamwater chemistry (Currey, 1970; Banens, 1987), although land use (Walling and Webb, 1975) and rainfall (Yu and Neil, 1993b) may be a factor within catchments and, where solute concentrations are low, atmospheric accession may play an important role in some coastal catchments (Douglas, 1968; Bayly and Williams, 1973; Cornish and Binns, 1987). It seems likely that all of these factors apply in the Tully catchment, as the evidence from long profiles of solute concentrations suggests.

3.10 SPATIAL VARIATION IN WATER QUALITY, TULLY RIVER CATCHMENT:

3.10.1 Introduction:

In order to determine the spatial patterns of water quality in the Tully River catchment, a programme of sampling tributaries to the main stem, as outlined in Chapter 3.2.1, was undertaken. Forty-six sites were sampled on 15 occasions during the 1987-88 sampling period. The sampling scheme used is similar to that of Walling and Webb (1975), but in this case fewer sites and more frequent observations are used.

For a substantial part of the 1990 sampling period, flooding in the Tully River catchment made most of the sampling sites on tributaries inaccessible. As a result, no sampling of spatial variability in the Tully catchment was undertaken during this period. Sampling sites in the Banyan Creek catchment were accessible at most times during March-April, 1990 and sampling was continued at these sites. Banyan Creek results are presented in Chapter 3.11.

3.10.2 Suspended sediment:

The 46 subcatchments of the Tully basin which were sampled 15 times during 1987-88 were subdivided into five terrain classes, defined by lithology, land use and topography. As discussed previously, these catchment characteristics are quite strongly inter-related in the Tully basin. Descriptions of the classes used are as follows:

i. Alluvial plain , predominantly under cropland (n=15).
ii. Alluvial plain, predominantly under pasture (n= 8).
iii. Alluvial plain, poorly drained swampland and pasture (n= 4)
iv. Montane granitic, predominantly under rainforest (n=11).
v. Montane rhyolitic, predominantly under rainforest (n= 8).

Although the peak stream discharges during this sampling period were much lower than during the 1990 wet season, stream stage at Site 15 (Fig. 3.2.2) ranged from 8% - 40% of bankful during the 1987-88 season. This site was chosen as an index of stage height as its configuration permits accurate stage measurement. Stage at this site is reasonably well correlated with that at other sites in the Tully catchment for the times of observation, as shown in Table 3.10.1.

Site	15	29	31	40	43	55
15	1					
29	.858	1				
31	.968	.926	1			
40	.945	.819	.911	1		
43	.947	.717	.917	.914	1	
55	.779	.637	.703	.661	.637	1

Table 3.10.1
Correlation matrix showing the interrelationships of stage at six Tully catchment sites for 15 observations.

Like most hydrological data sets, however, observations at low flows predominate. There is a cluster of observations at the low end of the observed flow range, another cluster at about the middle of the range, and a single observation at higher discharge.

The relationship between stage and the median SSC observation for sites within the alluvial plain terrain classes is shown in Figs. 3.10.1 (a), and for montane catchments in Fig. 3.10.1 (b) in relation to stage at Site 15. SSC increases with flow, as expected. The terrain classes fall quite clearly into two groups - the alluvial plain catchments and the montane catchments, with the former having higher SSC throughout the streamflow range. The SSC of the two montane groups is similar at low flows, although granitic catchments do have slightly lower sediment concentrations. As stage increases the granitic catchments appear to have marginally higher sediment concentrations than do those on rhyolite.

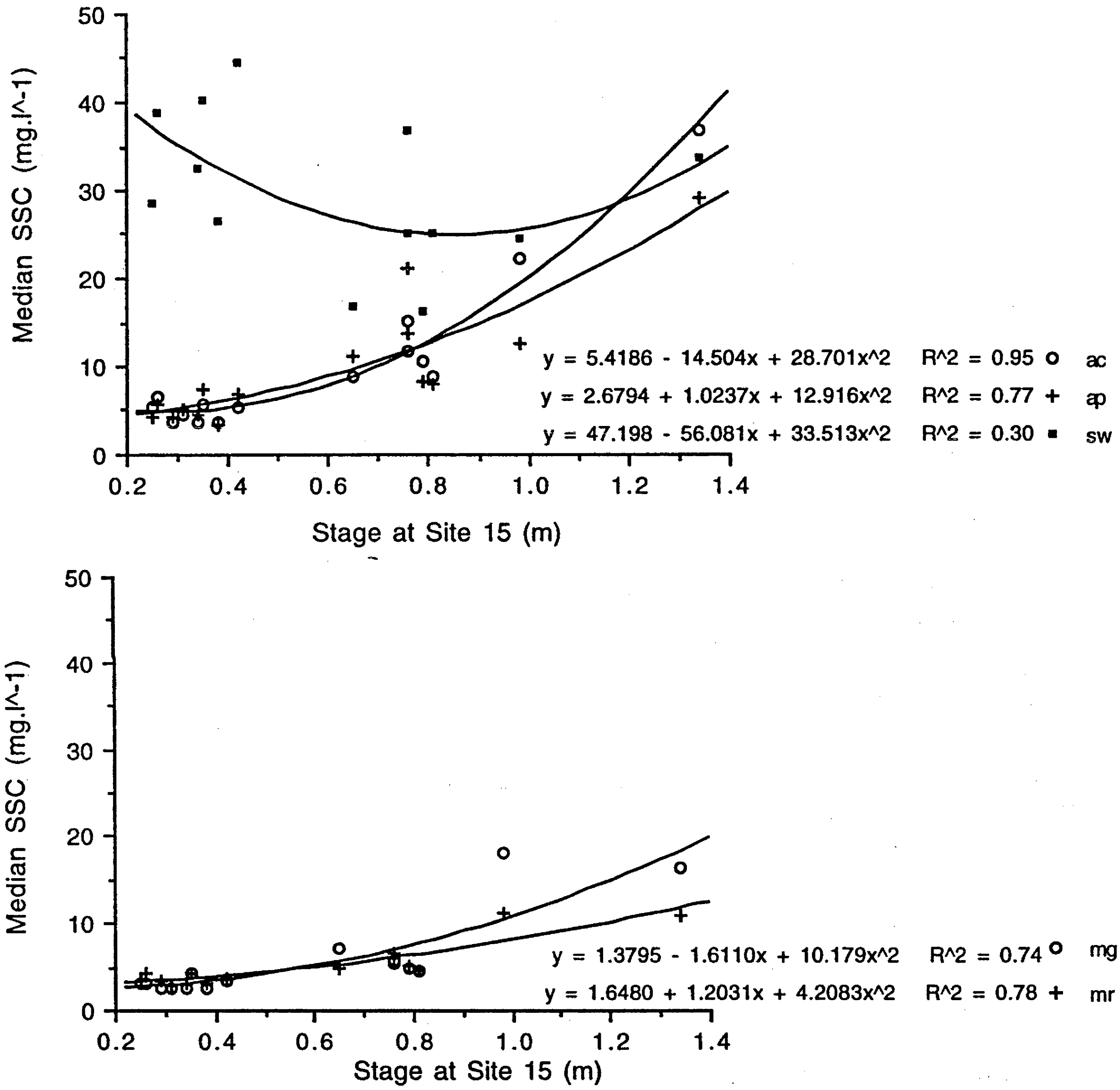


Fig. 3.10.1
Suspended sediment concentration in relation to stage at Site 15 for four terrain types (15 observations for 46 subcatchments).
(a; top)
ac - alluvial plain cropland; n = 15 catchments.
ap - alluvial plain pastureland; n = 8.
sw - alluvial plain swampland; n = 4.
(b; bottom)
mg - montane granite under rainforest; n = 11.
mr - montane rhyolite under rainforest; n = 8

The poorly drained swampy catchments have relatively high sediment loads at low streamflows. It is likely that high levels of productivity are maintained in these warm, shallow, relatively stagnant swamps and these productivity levels are enhanced by the aerial application of fertiliser, predominantly superphosphate. Some sediment resuspension probably occurrs due to trampling by livestock. Consequently, at low discharges there is a steady export of, largely organic, particulates. During runoff events, however, the organic particulates are rapidly flushed from the system and inorganic soil erosion products predominate. There is some indication of this in the decline in SSC with increasing streamflow and then an increase to approximately the same level as other subcatchments under pasture at the highest observed discharges. No analyses of suspended particulates were undertaken to confirm this interpretation. The high particulate loads observed at low Q from these catchments are unlikely to have any significant effect on the overall sediment yield of the catchment. Comparison with topographically similar sites where drainage works have been carried out indicates that land use change may have reduced particulate loads from some areas of the catchment at low flows.

The relationship between suspended sediment concentrations in tributary streams to the Tully River and the proportion of land cleared in each subcatchment is significant ($p \leq 0.05$) in 13 of the 15 observations. However, in only one case does the variance explained exceed 50%. For these analyses the swampland catchments are omitted as their hydrological and sediment transport characteristics are clearly atypical. For all significant relationships the slope was positive, confirming a general increase in the particulate concentration with area cleared.

The data set was subdivided into two sets :- the eight observations at low flow and seven at higher stage. The median SSC for each of the 42 sites was calculated and regressed against % area cleared. Median values were used in order to reduce the effect of outliers on the results. Although specific outcomes may be changed by the use of medians instead of means (e.g. the coefficients of a regression equation), the general relationships and conclusions presented in this and subsequent sections do not change. The relationships between median SSC and % cleared are as follows (only the third of these relationships is significant ($p \leq 0.05$)):

Low stage SSC = 2.595 + 0.065. % area cleared; $R^2 = 0.176$ [Eqn. 3.10.1]

High stage SSC = 5.584 + 0.226. % area cleared; $R^2 = 0.295$ [Eqn. 3.10.2]

All observations SSC = 3.581 + 0.079. % area cleared; $R^2 = 0.310$ [Eqn. 3.10.3]

Other catchment variables were tested, including catchment area, relief, percent slope and length of unsealed roads.km^{-2} in the catchment. In general, less than half the variance explained by the % area cleared is explained by these variables. Neither do they significantly improve the relationship between SSC and % cleared. Partial correlation coefficients for these variables are set out in Table 3.10.2.

Variable	Partial correlation		
	Low stage	High stage	All observations
Catchment area	- 0.084	0.159	0.038
Catchment relief	- 0.139	- 0.025	- 0.034
Percent slope	0.001	- 0.243	- 0.113
Unsealed roads . km^{-2}	- 0.203	- 0.128	- 0.291

Table 3.10.2
Partial correlation coefficients for catchment variables in relation to SSC; Tully River catchment.

In virtually every case, the sign of the slope coefficient is contrary to that which would have been expected, and supports the general conclusion that land use is regionally more significant than natural catchment characteristics in determining suspended sediment concentrations.

For cropland on alluvium terrain, the mean area cleared is 36 ± 20 %. Suspended sediment concentration is correlated with % area cleared for this terrain type:

Low stage SSC = 1.384 + 0.076. % area cleared; $R^2 = 0.439$ [Eqn. 3.10.4]

High stage SSC = 5.692 + 0.224. % area cleared; $R^2 = 0.153$ [Eqn. 3.10.5]

All observations SSC = 2.442 + 0.090. % area cleared; $R^2 = 0.506$ [Eqn. 3.10.6]

The first and third of these relationships are significant ($p \leq 0.05$), the second is not. The coefficients for these equations are consistent with those for the complete data set given above. There is no significant relationship between % cleared and SSC for the eight sites in the pasture on alluvium terrain class. This may indicate that the pasture cover is of sufficient quality, or was at the time of sampling, to minimise soil losses by sheet erosion. The sediment concentrations observed may, to the extent that they exceed those from the montane forested catchments (Fig. 3.10.1 (a) and (b)), represent the contribution of bank erosion from incised channels meandering across the alluvial plain. Although degradation of streambanks in the course of land clearing, for both agriculture and pasture, is widespread in the Tully catchment, it is not clear from the data how much of the bank erosion can be attributed to human interference. Natural, uncleared channel banks support a dense riparian rainforest which would minimise abrasion of bank sediments, although failure of vegetated stream banks does occur, predominantly by undercutting of the unvegetated deposits below baseflow stage. The stability of the vegetated stream banks and the general field observation that active bank erosion is generally apparent only where banks have been cleared, supports the conclusion that most of the bank erosion can be attributed to this cause.

There is no clear evidence of the effect on suspended sediment concentrations of land use change to pasture on the alluvial plain, although an increase by a factor of 2 seems a realistic estimate. There is an insufficient range of % area cleared in the two montane terrain classes to estimate the effect of land clearing therein. They are useful here as an indication of the SSC in the montane streams, relative to those of streams of the alluvial plain.

3.10.3 Dissolved solids:

Solute loads were determined using the same samples as those for suspended sediment concentrations described above. Stream TDS is inversely related to streamflow (Fig. 3.10.2 (a) and (b)), following the expected pattern for a relatively coarse data set such as this. Clearly there is no way to incorporate hysteretic TDS / Q relationships with this type of data. Apart from the general trend in relation to discharge, the TDS data for this broad scale spatial survey follow a generally similar pattern to that evident for SSC. The solute loads for the two montane, forested terrain types are always lower than for the alluvial plain catchments, for a given discharge. At low discharges the alluvial plain swamplands have much higher solute concentrations than for cropland or pasture. This is attributed to the same conditions of drainage from eutrophic swamps as contributed to the high SSC levels in these catchments at low discharges. At increasing discharges, cropland solute concentrations exceed those from pastureland and swampland solute concentrations are similar to those from pasture.

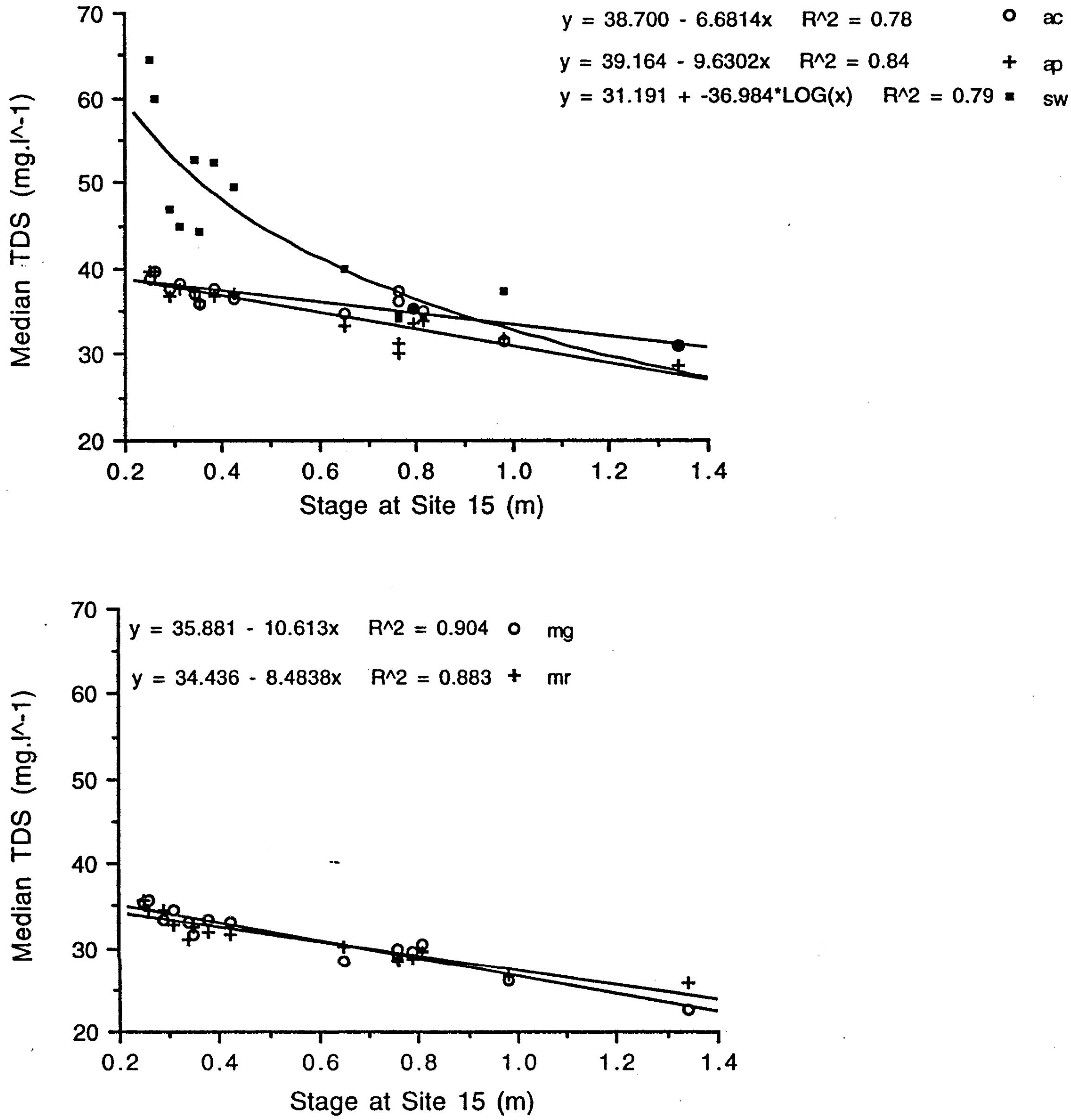


Fig. 3.10.2
Solute concentration in relation to stage at Site 15 for four terrain types (15 observations for 46 subcatchments).
(a; top)
ac - alluvial plain cropland; n = 15 catchments.
ap - alluvial plain pastureland; n = 8.
sw - alluvial plain swampland; n = 4.
(b; bottom)
mg - montane granite under rainforest; n = 11.
mr - montane rhyolite under rainforest; n = 8

Although there is clearly no difference between solute loads of catchments on rhyolite and those on granite, these montane catchments have lower solute concentrations than those on the alluvial plain at all stages observed.

Although the effect of atmospheric accession can be neglected in relation to suspended loads (the incidence of dust storms in the study area is very low (McTainsh and Pitblado, 1987; McTainsh *et al.*, 1989)), it was demonstrated in Chapter 3.4.3 that this is not the case for solute loads. If it is assumed that atmospheric accession is linearly related to the natural logarithm of the distance from the coast, then estimates of the inputs to each catchment can be readily made using the data from Tully and Cardstone. Mean accession rates for the four terrain classes are 73.4 (cropland on alluvium), 42.2 (pasture on alluvium), 48.6 (swampland), 46.2 (montane granite) and 28.8 $t.km^{-2}.yr^{-1}$ (montane rhyolite). This suggests that some of the differences in solute loads between terrain types could well be related to rates of atmospheric accession. Such a difference would tend to reduce the difference between pasture and cropland and between alluvial plain and montane catchments.

Comparison of the estimated accession with solute load for individual catchments shows that there is a significant ($p \leq 0.05$), positive relationship with the mean solute concentration for the eight high discharge observations, but the relationship is not significant for the mean of the low flow observations. However, multiple regression shows that estimated atmospheric inputs do not significantly improve the relationship between the catchment area cleared (%) and the solute concentration.

Of the catchment characteristics evaluated, the area cleared is the best correlate of solute concentration. This relationship is significant ($p \leq 0.05$) in the comparison with the median solute concentration for the eight low Q observations, the high Q observations and the median of all 15 observations. The slope of the regression is greater for low flow observations than for those at relatively high flows. Land use, therefore, appears to be a major determinant of solute loads in the Tully catchment. Lithology and atmospheric accession probably play some subordinate role. The relationships between median TDS and % cleared for the 46 observations are as follows (all of these relationships are significant ($p \leq 0.05$)):

Low stage TDS = 32.866 + 0.122. % area cleared; $R^2 = 0.176$
[Eqn. 3.10.7]

High stage TDS = 28.034 + 0.130. % area cleared; $R^2 = 0.295$
[Eqn. 3.10.8]

All observations TDS = 30.788 + 0.107. % area cleared; $R^2 = 0.310$
[Eqn. 3.10.9]

The other catchment variables tested were poorly correlated with solute concentration and, with the exception of catchment relief, do not significantly improve the relationship between TDS and % cleared. Partial correlation coefficients for the stepwise regression are set out in Table 3.10.3.

Variable	Partial correlation		
	Low stage	High stage	All observations
Catchment area	0.08	-0.029	0.101
Catchment relief	- 0.313	- 0.354	- 0.240
Percent slope	0.273	- 0.154	- 0.238
Unsealed roads . km^{-2}	- 0.059	0.074	0.099
Atmospheric accession	-0.049	0.282	0.121

Table 3.10.3
Partial correlation coefficients for catchment variables in relation to TDS; Tully River catchment.

The best predictor of TDS in Tully catchment streams, at both high and low flows, is the combination of the percent area of catchment cleared and the catchment relief (Table 3.10.4). The decline in solute load with increased relief is likely to be the result of greater overland flow relative to throughflow, and to the postulated decline in atmospheric accession with elevation.

There is a similarity between SSC and TDS as they relate to area cleared within terrain classes. For the alluvial cropland there is a significant ($p \leq 0.05$) relationship between TDS and % cleared at high flows and for the median of stage for the 15 observations, but at low flows the relationship is not significant. There is no relationship between % cleared and TDS in the alluvial pasture terrain class. Interpretations generally similar to those for SSC patterns may be made of these results. Higher solute loads occur in streams on the alluvial plain than from the montane catchments because of the greater proportion of streamflow derived from throughflow in the former terrain. On the alluvial plain, solute concentrations at low flows are similar for both terrain classes. As streamflow increases, with a greater proportion derived from surface runoff processes, solute loads from cropland exceed those from pasture as a result of the higher levels of soluble fertilisers applied to the cropland. These interpretations are tentative and require detailed process studies to confirm them.

Variable	Value	Standard error	Error probability	R^2	Error probability (F-test)
Dependent variable - TDS at low flow				0.291	0.0012
Intercept	36.603				
% Cleared	0.102	0.037	0.009		
Relief (m)	- 0.005	0.002	0.046		
Dependent variable - TDS at high flow				0.521	0.0001
Intercept	30.623				
% Cleared	0.116	0.022	0.0001		
Relief (m)	- 0.003	0.001	0.023		

Table 3.10.4
Parameters of the model of TDS in relation to catchment characteristics; Tully River catchment; n = 46.

3.10.4 Natural variability:

The inherent variability of geomorphic processes in both space and time has important consequences when comparing the relationship of catchment characteristics to denudation rates. In comparisons of stream loads (both particulate and solute) for catchments of differing characteristics, there is frequently the implicit assumption that, given consistent patterns of physiography and land use, similar denudation rates will apply.

To assess the role of natural variability between subcatchments, a set of catchments with the minimum degree of variability of morphology and land use was identified from each of the four major terrain types defined (i.e. excluding the swampland class). This entailed the removal of 50% of all catchments from the data set, with about half the sites from each terrain class considered sufficiently similar to warrant inclusion. The characteristics of these catchments are set out in Table 3.10.5.

Because both particulate and solute concentrations are strongly correlated with streamflow it is also desirable to compare observations made within a narrow discharge range. The eight low flow observations described above fall within a narrow stage range. Stage measurements at six sites, widely distributed throughout the catchment (those listed in Table 3.10.1 above), had mean stream depths as follows: Site 15 (0.305 $\pm$ 0.059 m), Site 29 (0.126 $\pm$ 0.068), Site 31 (1.230 $\pm$ 0.044), Site 40 (0.204 $\pm$ 0.027), Site 43 (0.070 $\pm$ 0.023) and Site 55 (0.400 $\pm$ 0.099).

Catchment characteristic	Alluvial plain, cropland	Alluvial plain, pastureland	Montane, granite	Montane, rhyolite
n	7	4	6	4
% cleared	41.3 ± 20.8	17.8 ± 10.6	0	4.75 ± 3.0
Area (km^{-2})	9.59 ± 5.8	26.6 ± 20.8	2.7 ± 2.0	2.4 ± 1.8
Relief (m)	557 ± 77.5	862 ± 259	550 ± 227	756 ± 263
% slope	0.112 ± 0.04	0.101 ± 0.03	0.169 + 0.04	0.24 ± 0.05
Unsealed road. km^{-2}	0.391 ± 0.17	0.039 ± 0.05	0	0
Atmospheric accession ($t.km^{-2}.yr^{-1}$)	27.3 ± 1.49	17.4 ± 3.3	12.0 ± 17.0	15.0 ± 0.36

Table 3.10.5
Characteristics of sub-catchments in four terrain classes in the Tully River catchment.

In spite of this high degree of consistency of both catchment characteristics and stream flow the median suspended sediment concentrations for 8 observations at the six 'consistent' sites in the alluvial cropland class ranged from 2.2 to 7.0 $mg.l^{-1}$. This range represents 62 % of the range for all sites (15) in this class. In the case of solute concentrations, the range of the consistent catchments, 32.0 to 44.4 $mg.l^{-1}$, is about 48 % of median TDS observations for all sites in the class.

The catchments selected as the most consistent in the alluvial plain pastureland class have median values which cover the entire range of both SSC and TDS for subcatchments in the class, and this is also the case for the montane granite catchments. The median SSC values for the four similar catchments in the montane rhyolite class cover 100 % the range for the eight sites in the class, and TDS medians for the the similar sites cover 78 % of the class range.

These results suggest that a substantial component of inter-catchment variability in stream loads can simply be attributed to the inherent variability in erosion and transport processes. The similar sites in both of the montane terrain types have less variability than do those from the alluvial plain sites and are relatively close together in space. Regardless of this, the range of median particulate concentrations observed in similar montane granitic sites represent 19 % of the entire range for the subcatchments within the Tully basin, excluding the swampland class. For similar montane rhyolite sites their range of medians is 39 % of those for the entire basin. Including the swampland class, with their atypical behaviour at low streamflows, 8 % and 16 % of the catchment-wide range is contained within the similar montane granite and rhyolite catchments, respectively.

Solute concentrations follow a similar pattern. Fourteen percent of the range of site median TDS values observed for all sites in the Tully basin is found in the six similar montane granite catchments and 10 % in the case of the four rhyolite catchments. These patterns of variability are illustrated in Fig. 3.10.3 for both SSC and TDS.

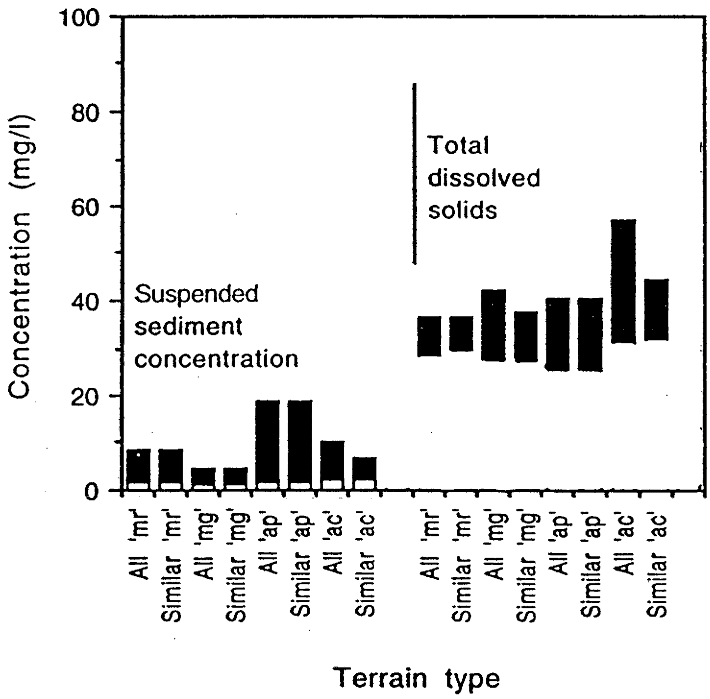


Fig. 3.10.3
Diagram showing the range of site median values for each terrain type and the range for similar sites within each terrain type. The range for each terrain type lies within the upper and lower bounds of the black bar.

This degree of variability in catchments of similar morphology and land use implies that interpretations of differences in sediment yield and water quality are likely to be subject to considerable error due to factors which are not necessarily known or easily measured. In the foregoing analysis this problem is reduced by the large number of subcatchments used. It is of greater significance in the following, more detailed analysis of water quality in relation to land use in Banyan Creek, in which a relatively small number of sites was monitored.

3.11 SPATIAL VARIATION IN WATER QUALITY IN BANYAN CREEK CATCHMENT:

3.11.1 Introduction:

Using the same general approach to assessment of spatial variation in water quality as used by Walling and Webb (1975) and in the wider Tully catchment, spatial variation of water quality in the Banyan Creek catchment was assessed at nine sites. Samples from these sites were obtained on 58 occasions during the 1987-88 sampling period and on 25 occasions during the 1990 sampling period. The high degree of consistency between observations for a given site at low streamflows was noted early in the sampling period. Consequently, sampling at higher flows was carried out at disproportionate frequencies in order to ascertain the variation in catchment response over a wide range of hydrological conditions.

The pattern of streamflow in the Banyan Creek catchment during the two sampling periods is essentially the same as for the Tully River. Maximum stage during the 1987-88 sampling period was equivalent to about 40 % of channel depth in Banyan Creek (at Site 16), and during 1990 stage at > 95 % of channel depth was recorded. At Site 10 the datum point on the bridge was overtopped by c. 1.4 m and the bridge was sufficiently damaged to require closure to vehicular traffic. Another datum point on an undamaged part of the bridge was then chosen, with the probability of some subsequent errors in stage measurement. At Site 17 Banyan Creek broke its banks and overtopped the datum by approximately 0.2 m. As a result, errors also arise at this site in the determination of Q for the two largest flows sampled.

3.11.2 Consistency of observations:

The observations of SSC and TDS in the Banyan Creek catchment were not random in time. Deliberate oversampling of high flow events was carried out in order to obtain water quality data representative of the entire range of runoff conditions. It is therefore of some interest to ascertain the degree of consistency between observations of Q, SSC, and TDS. To this end correlation matrices of the relationships between data sets from each site were prepared for discharge, suspended sediment concentration and total dissolved solids observations.

There is a high degree of consistency in Q within sets of observations. The correlation matrix presented in Table 3.11.1 illustrates this and indicates that Walling and Webb's (1975) sampling strategy for base flow observations may be successfully extended to floodflows providing a large number of observations are made and the internal consistency of the observations is confirmed. All of the relationships are significant ($p \leq 0.05$), with that between the two largest catchments (adjacent Sites 16 and 17) being the best correlated. Not surprisingly, the smaller catchments are not as well correlated with each other, and are not well correlated with the two larger catchments. The observed strong relationships between sites do not mean that the problem of a lower probability of sampling the discharge or sediment load peaks in the smaller catchments, because of their shorter duration, does not occur. They do suggest, however, that the errors so induced will be acceptably low. Site 11 is excluded from this analysis as no stage data was collected there.

Site	10	12	13	14	15	16	17	18
10	1							
12	.864	1						
13	.898	.92	1					
14	.93	.958	.916	1				
15	.948	.927	.927	.974	1			
16	.846	.871	.818	.922	.903	1		
17	.826	.867	.811	.918	.896	.99	1	
18	.935	.898	.912	.933	.961	.859	.854	1

Table 3.11.1
Correlation matrix for paired streamflow observations at Sites 10 - 18.

As a simple check on the internal consistency of turbidity/SSC observations at the Banyan catchment sites, the correlation matrix shown in Table 3.11.2 was prepared. In all cases the correlations are positive and significant ($p < 0.05$). However, in some cases the relationship has little predictive value. The greatest inconsistencies lie in the comparison of the smallest and largest catchments and, given a range of catchment sizes from 2.4 to 126 km^2, this is not a surprising outcome.

The internal consistency of the conductivity/solute concentration observations was tested in the same manner as were the discharge and turbidity data sets. Table 3.11.3 shows the correlation matrix for observations at Sites 10 - 18 during 1987-88 and 1990 sampling periods. All data sets have strong, significant ($p< 0.05$) mutual correlations, generally stronger than those for either discharge or turbidity.

Site	10	11	12	13	14	15	16	17	18
10	1								
11	.796	1							
12	.94	.874	1						
13	.755	.938	.869	1					
14	.859	.806	.883	.752	1				
15	.827	.855	.863	.822	.962	1			
16	.598	.226	.591	.245	.538	.436	1		
17	.661	.374	.622	.34	.75	.699	.837	1	
18	.767	.852	.796	.811	.824	.871	.39	.577	1

Table 3.11.2
Correlation matrix for paired turbidity/SSC observations at Sites 10 - 18 (n = 83).

Site	10	11	12	13	14	15	16	17	18
10	1								
11	.881	1							
12	.976	.925	1						
13	.86	.957	.928	1					
14	.931	.95	.964	.95	1				
15	.873	.968	.925	.966	.972	1			
16	.919	.911	.941	.896	.935	.918	1		
17	.864	.893	.905	.894	.9	.901	.975	1	
18	.888	.926	.928	.931	.941	.948	.897	.874	1

Table 3.11.3
Correlation matrix for paired conductivity/TDS observations at Sites 10 - 18 (n = 76).

The average value of the correlation coefficient 'r' for the 28 possible combinations of Q observations is 0.903 (c.v. = 5.2%) suggesting a high level of consistency between observations. For TDS the mean is 0.923 (c.v. = 3.6%; n=36). On the other hand, the mean for SSC is only 0.771 (c.v. = 28.4%; n=36). This result is indicative of a high level of spatial coherence and stability in both discharge and TDS, which permits relatively simple and reliable monitoring of both and some ability to both interpolate and extrapolate results. Suspended sediment concentrations behave in a much less coherent and stable manner as a result of greater complexity in the transport processes and variability in the source areas in both space and time. Walling and

Webb (1983) investigated the relative variability of suspended and dissolved streamloads and also found that sediment loads exhibited greater variability and were more responsive to inter-annual runoff variations and extreme events. These results are a confirmation of that conclusion.

Examination of the relationship between correlation coefficients for the SSC and TDS data sets indicates that there is some consistency between them (i.e. the catchment pairs which exhibit strong inter-relationships in SSC also do so with respect to TDS).

These observations suggest that the approach to water quality monitoring used in this study is reliable for spatial analysis of solute concentrations, but in the case of suspended particulates the errors are likely to be greater.

3.11.3 Suspended sediment:

The sites selected for intensive sampling in the Banyan Creek catchment were chosen in order to obtain a wide range in the proportion of each subcatchment which had been cleared for cultivation, predominantly of sugar cane. The nature of agricultural production is such that some degree of interdependence between catchment physiography and patterns of land use is inevitable. Site selection was based on a deliberate attempt to maximise the independence of catchment characteristics. This was only partially successful.

The variations in SSC measured at the selected sites were assessed in relation to the catchment characteristics defined in Table 3.11.4. The table also includes a correlation matrix showing that, in Banyan Ck., these catchment characteristics are independent of each other, with the exception of the '% cleared' and '% transported soils' categories which are significantly, positively correlated ($p \leq 0.05$).

	Variable	1	2	3	4	5
1	% Cleared	1.0	-	-	-	-
2	Catchment area	0.31	1.0	-	-	-
3	% Slope	- 0.61	- 0.17	1.0	-	-
4	Unsealed roads ($km.km^{-2}$)	0.28	- 0.17	- 0.22	1.0	-
5	% Transported soils	0.77	0.26	- 0.41	0.37	1.0

Table 3.11.4
Correlation matrix of catchment variables used in streamwater analyses for the Banyan Ck catchment.

The individual catchments exhibit a considerable degree of variability in their general characteristics (Table 3.11.5), which is desirable if they are to be used to assess their relationship with water quality. For convenience, the sites numbered 10 to 18 are ranked in order of increasing percentage area cleared.

Site	Percent cleared	Catchment area (km^{-2})	Percent Slope	Percent transported soils	Unsealed roads ($km.km^{-2}$)
10	1	31.55	14.2	9.7	0.11
11	8	4.975	10.3	51.7	0.23
12	12	3.6	15.1	43.0	0.15
13	17	2.4	15.9	35.2	0.41
14	19	5.55	14.6	31.6	0.01
15	34	7.05	7.7	30.2	0.16
16	36	126.02	8.7	52.1	0.17
17	50	65.8	13.0	77.2	0.18
18	56	4.6	6.0	71.3	0.36
Mean	25.9	27.9	11.7	44.7	0.198
c.v. (%)	74	151	31	47	62

Table 3.11.5
Characteristics of Banyan Creek sub-catchments.

Mean suspended sediment concentrations at sites 10-18 for the 1987-88 sampling period range from 3.6 $mg.l^{-1}$ (Site 10) to 22.5 $mg.l^{-1}$ (Site 18). During the 1990 sampling period, SSC means were in the range 9.3 $mg.l^{-1}$ (Site 10) to 71.5 $mg.l^{-1}$ (Site 17). Median values for these data sets follow a very similar pattern; 1.8 to 9.6 $mg.l^{-1}$ (Sites 10 and 17; 1987-88) and 3.5 to 47.5 $mg.l^{-1}$ (Sites 10 and 17; 1990). The SSC averages for each site generally exhibit a strong correlation with the proportion of catchment cleared (Fig. 3.11.1). During the relatively high streamflows of the 1990 sampling period the slope coefficient of the relationship is greater by a factor of 5 than during the low flows observed during 1987-88.

There is no significant relationship with any of the other variables examined, with the exception of the '% transported soils' parameter which, as previously noted, is itself strongly correlated with landuse. Exploratory multiple regression analysis was undertaken to assess whether any of these variables gave a significant improvement in the relationship between land clearing and turbidity.

Catchment area is widely recognised as an important determinant of sediment yield. As catchment area increases there is generally a concomittant decline in the sediment delivery ratio (Roehl, 1962). A corollary of this is that steeper slopes trap less sediment and support higher flow velocities. Furthermore, higher rainfalls at higher elevations would

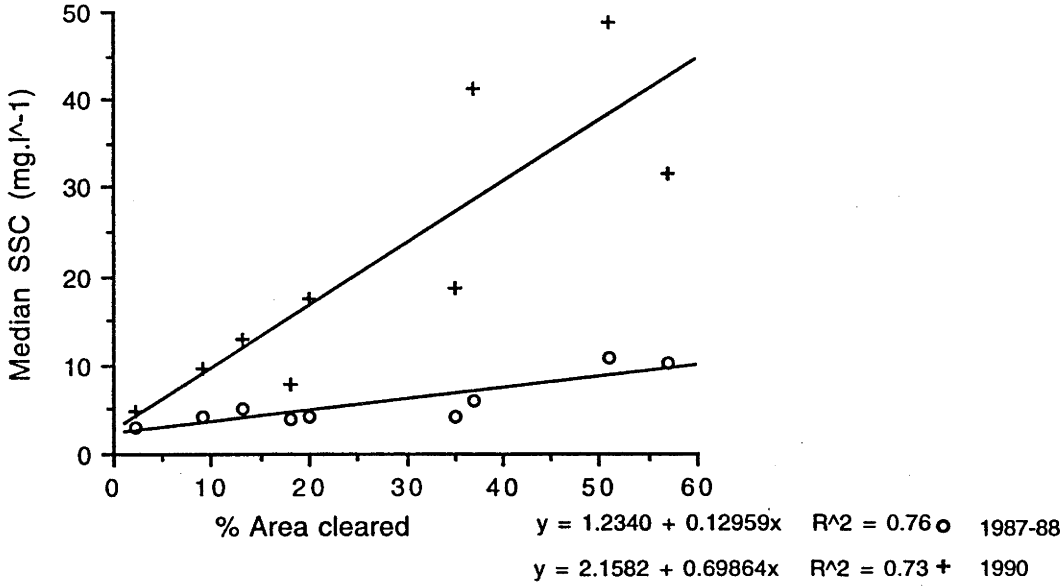


Fig. 3.11.1

Relationship of land use as proportion of catchment cleared to suspended sediment concentration for Sites 10 - 18;
1987-1988 sampling season - 58 observations;
1990 sampling season - 25 observations.

enhance the relationship between slope and sediment entrainment and transport. Therefore, some relationship between catchment morphology and sediment concentration in runoff waters would be expected. In the Banyan Ck catchment there is no evidence that either of the catchment morphology parameters is significant as even a secondary correllate of SSC.

In contrast to natural systems, when a catchment is geomorphically destabilised by extensive land use change the sediment concentrations and yields are likely to be dominated by the land use rather than morphology. This has been shown to be the case for small catchments on the Southern Tablelands of New South Wales, for example (Neil and Mazari, 1993).

The density of unsealed road networks in a catchment has been shown to be an important determinant of sediment yield (Reid and Dunne, 1984; El Swaify and Cooley, 1980; Bilby, 1985; Neil and Galloway, in prep.) and it is therefore surprising that unsealed roads appear to play no significant role in determining sediment concentrations in Banyan Ck streamwaters. There is no doubt that unsealed road runoff does contribute large quantities of sediment to streams, as the three random observations in Table 3.11.6 indicate.

Twenty-five samples of runoff from unsealed roads were collected with sediment concentrations ranging from 480 to 14 500 mg.l^{-1} ($\bar{x}$ = 2760; s.d. = 3620). By comparison, runoff from sealed roads has a $\bar{x}$ SSC of 51.1 mg.l^{-1}

(ranging from 2.4 to 308 $mg.l^{-1}$; n = 8). The duration of runoff from roads is quite short, generally very closely related to rainfall duration. Despite these high sediment concentrations the effect of unsealed road runoff is not evident in the overall data set.

SSC upstream of road input ($mg.l^{-1}$)	Mixing distance (m)	SSC downstream of road input ($mg.l^{-1}$)
2.0	100	17.0
6.0	30	16.4
30.2	40	65.7

Table 3.11.6
Increase in sediment concentration due to input of unsealed road runoff to stream waters.

The least squares regression equation describing the relationship between catchment percentage cleared and the median SSC for the 83 observations at Sites 10 - 18 has the form:

Median SSC = 1.82 + 0.19. % Cleared
(R^2 = 0.73; n = 9) [Eqn. 3.11.1]

Equations 3.11.2 and 3.11.3 indicate the nature of this relationship for the 1987-88 sampling period and the wetter 1990 period. The larger intercept value and slope coefficient for the latter period are in response to this difference in rainfall regimes.

Median SSC = 1.23 + 0.13. % cleared
(R^2 = 0.76; 58 obsv.; n = 9; 1987-88 data) [Eqn. 3.11.2]
Median SSC = 2.16 + 0.70. % cleared
(R^2 = 0.73; 25 obsv.; n = 9; 1990 data) [Eqn. 3.11.3]

These results indicate a significant decline in water quality as the proportion of catchment cleared of forest increases (Fig. 3.11.2). The relationship of cleared and cultivated land to topography is important in these results, as virtually all the cleared land in the Banyan Creek catchment lies on the alluvial plain where rates of soil erosion might be expected to be much lower than would be the case for the surrounding steeplands, should they be cleared. There is virtually no component of accelerated steepland erosion in Eqn. 3.11.1.

When individual sets of SSC observations are examined a similar pattern consistently occurs. Of the 58 sets of observations made in 1987/88, 79% exhibit a significant ($p \leq 0.05$), positive linear correlation between SSC and the percent area of land cleared. During 1990, 60% of the 25 observations exhibited such a relationship. As in the case of the site average sediment concentrations there is generally a poor relationship with the

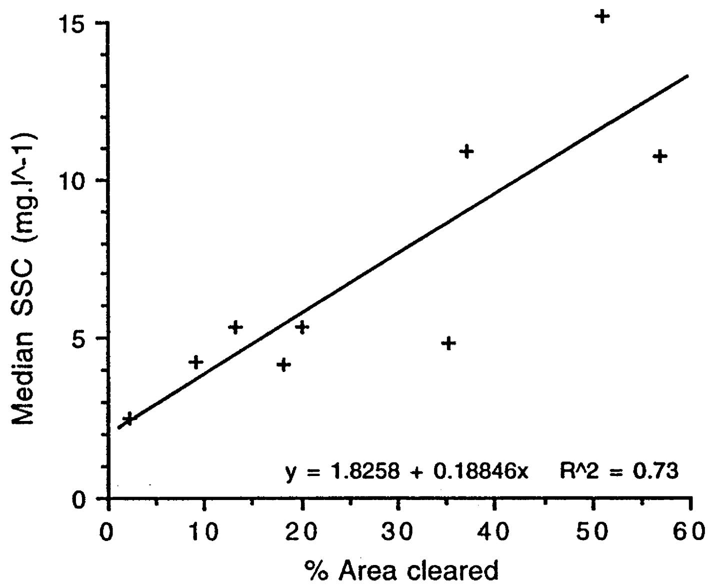


Fig. 3.11.2
Scatter plot showing the increase in median SSC with increasing proportion of catchment cleared for agriculture (each point is the median of 83 samples).

other variables tested, except for '% transported soils', for each of the 83 sets of observations. The results suggest that it is land use which is the major determinant of suspended sediment concentration in the Banyan Ck. catchment and that as much as an order of magnitude increase in sediment concentration may occur in catchments which are only 50% cleared for agriculture and where relatively undisturbed forest is retained on steeplands.

Suspended sediment concentration in streamwaters of the Banyan Ck. catchment is strongly related to stage in most cases. The relationship is significant ($p<0.05$) in all cases for linear regressions. Given that the observations cover virtually the entire range of probable stages for these subcatchments and, therefore, no extrapolation of the relationship is necessary, a 2nd order polynomial was fitted to take account of the non-linearity of the observed relationships (Table 3.11.7).

Observations of suspended load and of annual sediment yield series (van Sickle, 1981) generally exhibit a log-normal distribution. The problem of oversampling of low flow, low sediment concentration discharges is common in sediment yield studies and numerous approaches have been advocated for dealing with it. This data set is no exception. At Site 16, forexample, 57% of observations lie in the lower 10% of the stage range sampled, and only 4% lie in the upper 10% of the range. In relation to discharge, this ratio is far worse.

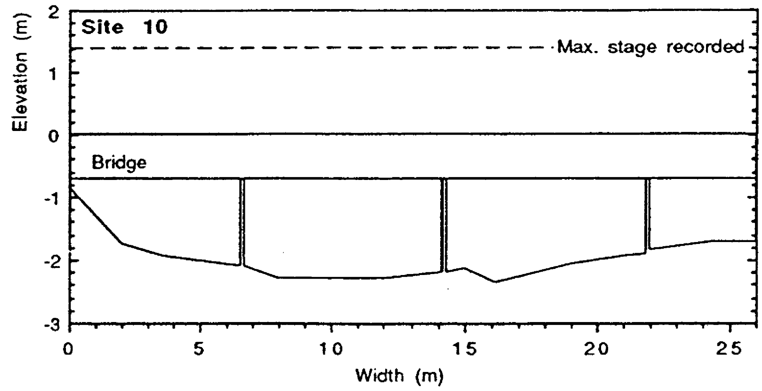
Site	n	S v SSC R^2 (linear)	S v SSC R^2 (2nd order polynomial)	s	'n'	*ln* Q v *ln* SSC R^2 (2nd order polynomial)
10	83	.686	.71	.003	.045	.702
12	81	.46	.798	.0028	.04	.737
13	59	.547	.937	.004	.04	.665
14	77	.682	.858	.0028	.04	.727
15	83	.756	.972	.0022	.04	.826
16	82	.277	.291	.001	.035	.573
17	82	.479	.481	.0013	.035	.616
18	77	.709	.781	.0022	.04	.581

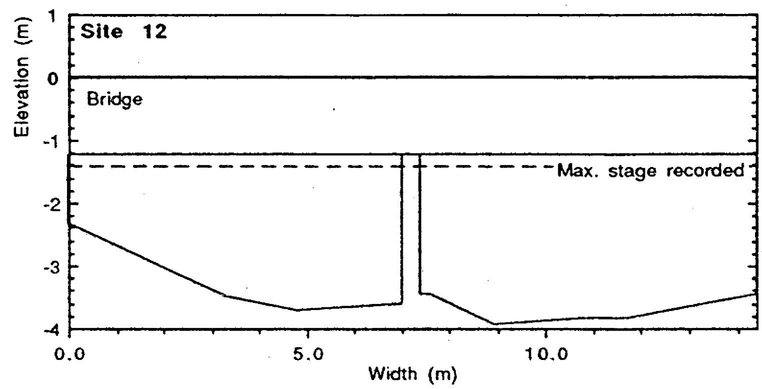
Table 3.11.7
Correlation between streamflow and SSC for subcatchments of the Banyan Creek basin.

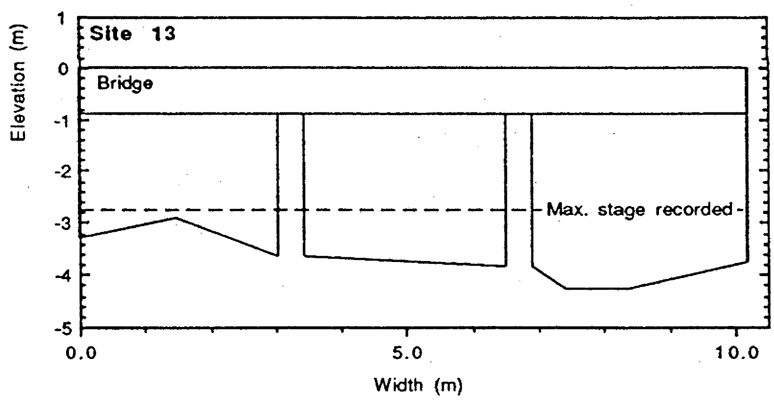
Estimates of discharge, using the methods described in Chapter 3.2.2, were calculated for the channel sections illustrated in Fig. 3.11.3. The presence of the bridge structure at each site compounds the errors inherent in the method. Sites 10 and 15 - 18 are essentially natural channels, although at Sites 15, 17 and 18 the banks have been deforested and are now vegetated with a dense grass cover. Bridge construction at Sites 12, 13 and 14 has entailed the replacement of the natural channel with concrete box culverts, but in each case substantial infilling with sediment, and subsequent revegetation has taken place, so that these sections resemble natural channels in many respects. The values of 'n' and s used in the computation of Q are given in columns 5 and 6 of Table 3.11.7.

Normalisation of the Q and SSC data by log transformation was carried out in order to better comply with the regression assumptions. Scatter plots of the relationship between log-transformed Q and SSC, for sites in the Banyan Ck. catchment, show that this relationship is non-linear (Fig. 3.11.4). Column 7 of Table 3.11.7 shows the R^2 values for 2nd order polynomial equations fitted to the transformed data.

In all cases the relationships are significant ($p \leq 0.05$) and discharge explains between 57 % and 82 % of the variance in SSC. This is in spite of the inability to separate rising and falling stage observations (in the absence of continuous stage recording), often an important factor in sediment rating curve construction (Walling and Webb, 1981). The correlation coefficients observed are probably as high as could be expected, given that sediment concentration generally peaks in advance of peak discharge and declines as sediment sources are depleted in spite of continued high runoff. Fig. 3.11.5. shows the extent to which inconsistencies between SSC and Q can occur.







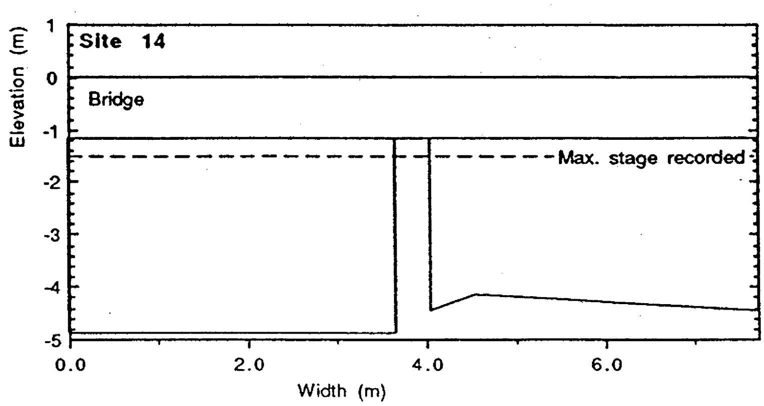


Fig. 3.11.3

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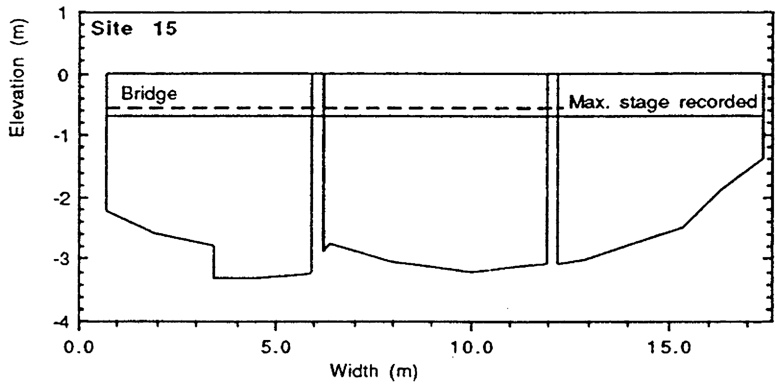

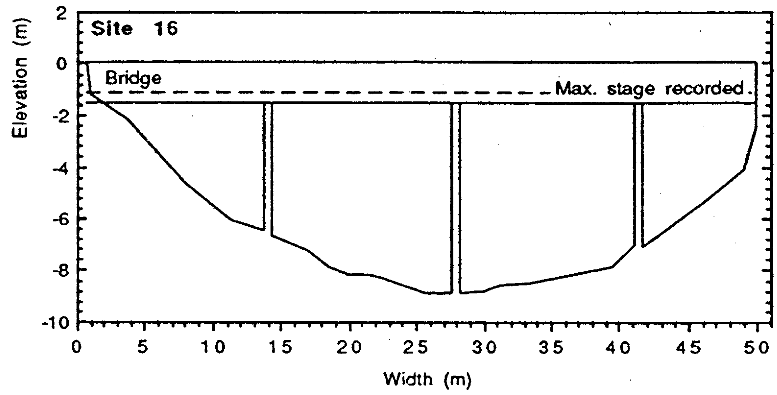

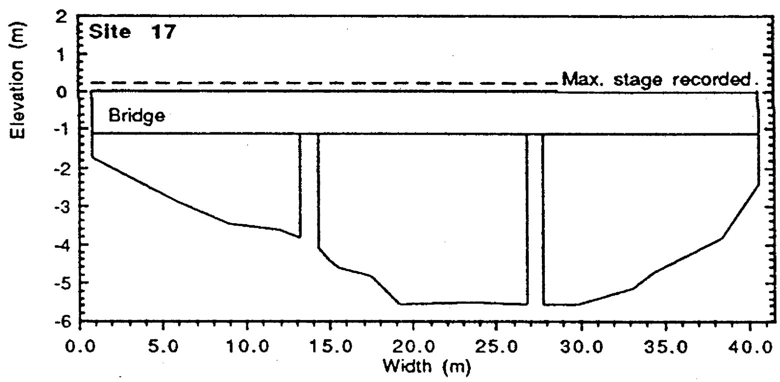

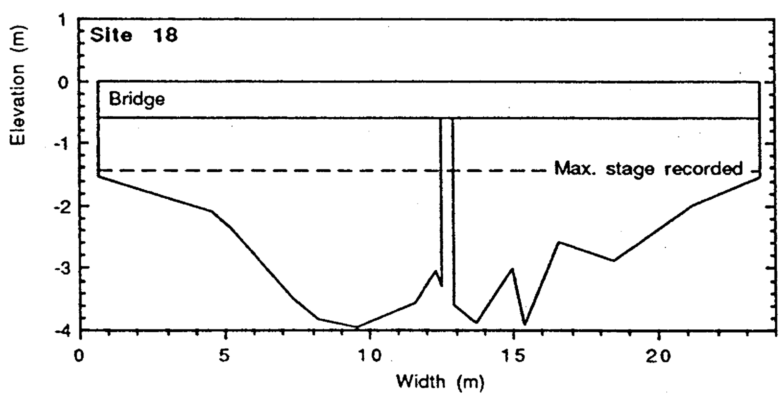

Fig. 3.11.3
Cross sections of stream channels in the Banyan Ck catchment. These cross sections are at the water sampling sites shown in Fig. 3.2.2 and are the sections for which streamflows were calculated.

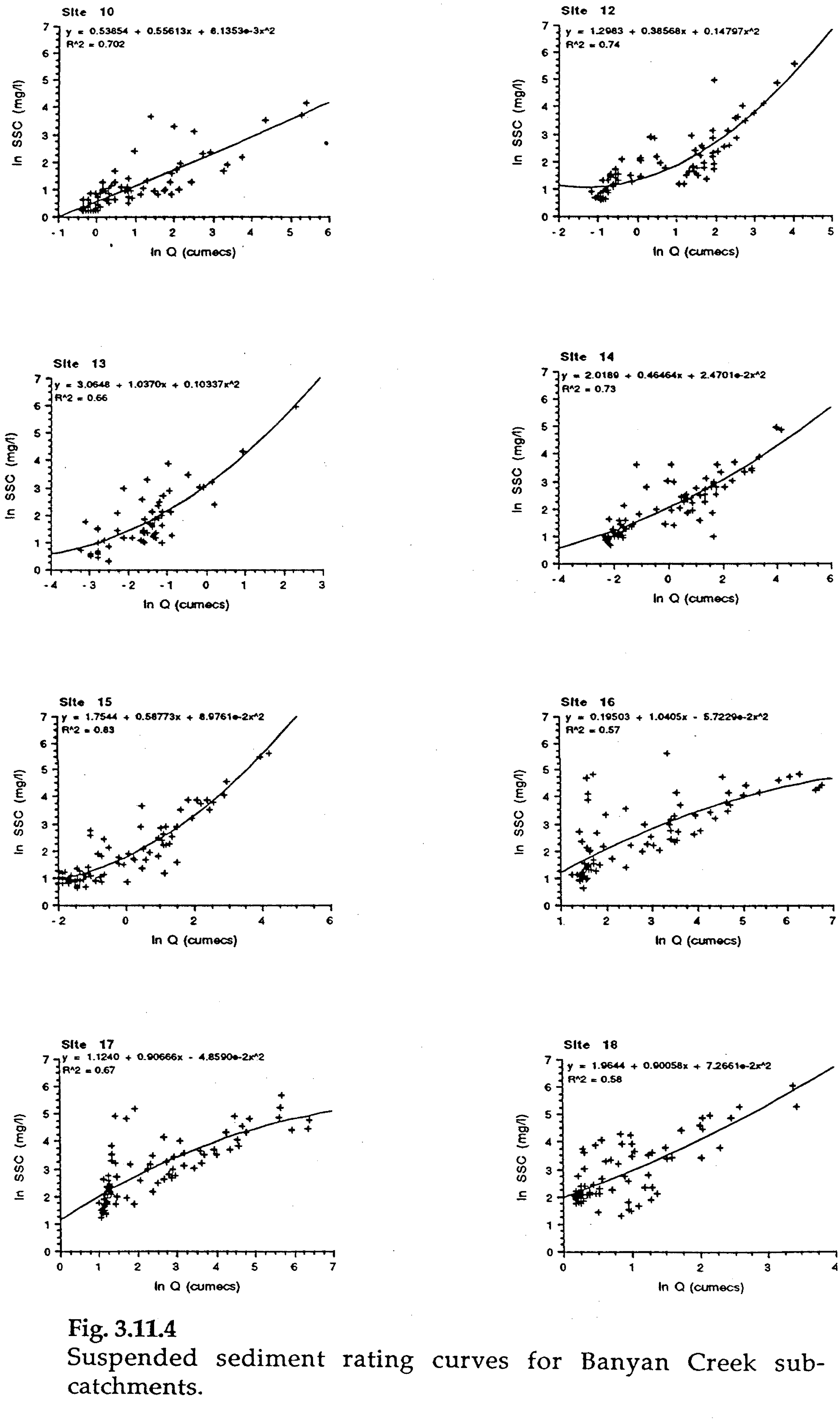

Fig. 3.11.4
Suspended sediment rating curves for Banyan Creek sub-catchments.

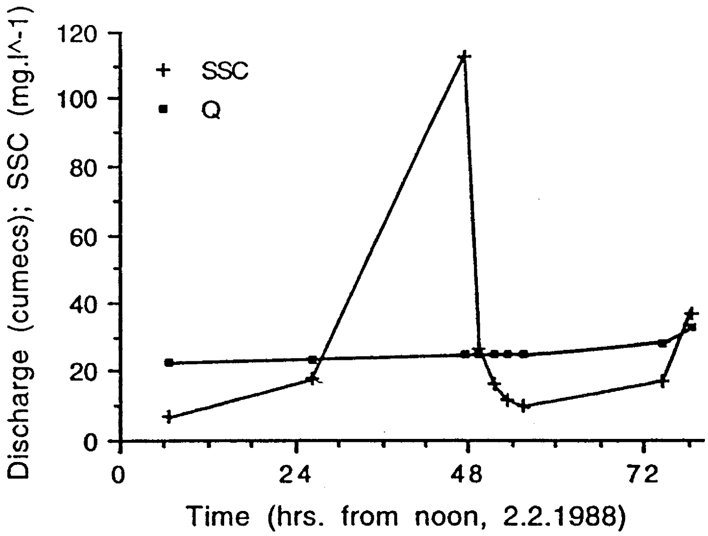

Fig. 3.11.5
Observations of Q and SSC at Site 16 showing variation in sediment concentration at constant discharge.

The correlation coefficient itself appears to be related to catchment area (Fig. 3.11.6) with the best fit of SSC to Q occurring in the smallest catchments. This pattern may well be explained by the tendency of smaller catchments, in this data set, to be more spatially homogenous in terms of rainfall, topography, lithology, soils and land use. In larger, more heterogeneous catchments the physiographic diversity may result in out of phase discharge and sediment concentration as a result of differential responses to rainfall events within the catchment. However, this relationship is not universal. The Tully River (1 475 km^2; $R^2 = 0.6$) does not comply with it and some small Snowy Mountains catchments exhibit inverse relationships between Q and SSC (Yu and Neil, in prep.).

The sediment rating equation of the form :

$$\ln SSC = a + b.\ln Q$$

can be rewritten as:

$$SSC = a.\ Q^b$$

The exponent of this relationship would be expected to increase significantly with the proportion of catchment cleared if land clearing and agricultural impacts are causing accelerated erosion. The relationship between 'b' and the % of catchment cleared is positive but is not significant ($p \leq 0.05$). This weak correlation may be partly attributed to the error associated with estimation of discharge.

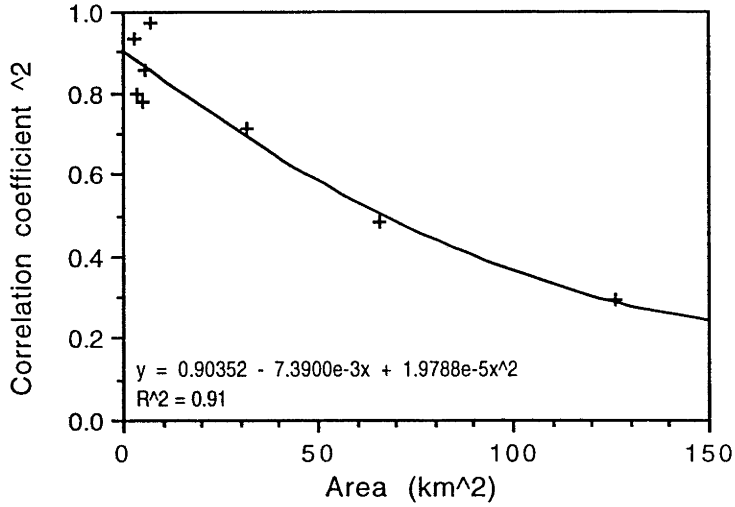

Fig. 3.11.6
Correlation coefficient (SSC v Q) in relation to catchment area.

3.11.4 Dissolved solids:

Conductivity determinations at Sites 10-18 spanned the range 12.2 - 47.9 uS.cm^{-1}, representing solute concentrations in the range 10.8 to 42.7 mg.l^{-1}.

There may be a decline in rainfall conductivity from east to west in the Banyan catchment due to the greater distance from the coast, but the catchment is relatively small and, on the basis of the atmospheric accession estimates derived for individual catchments, this difference would probably be small. Increased elevation in the western part of the catchment may also have some (unknown) effect on the spatial pattern of solute loads. The physiography of the Banyan Ck. catchment is such that the variation of atmospheric accession is unlikely to account for the spatial pattern of TDS.

During the relatively low discharges of the 1987-88 sampling period there is a poor relationship between median TDS and land use (Fig. 3.11.7) and during the 1990 sampling period there is no relationship between these variables. TDS is also poorly correlated with the other catchment characteristics investigated. Similarly, for the 76 individual sets of observations there is generally a poor correlation between solute concentrations and these catchment characteristics.

The high degree of internal consistency of the TDS observations suggests that the lack of an identifiable relationship with the catchment characteristics investigated is unlikely to be related to the sampling strategy used. Although lithology was a major determinant of spatial variation in solute concentrations in previous studies (eg. Walling and Webb, 1975) it is unlikely to be the cause of the observed pattern of solute concentrations in the Banyan catchment as the subcatchments with the highest and lowest median solute concentrations are immediately adjacent and have soils and sediments derived exclusively from granite.

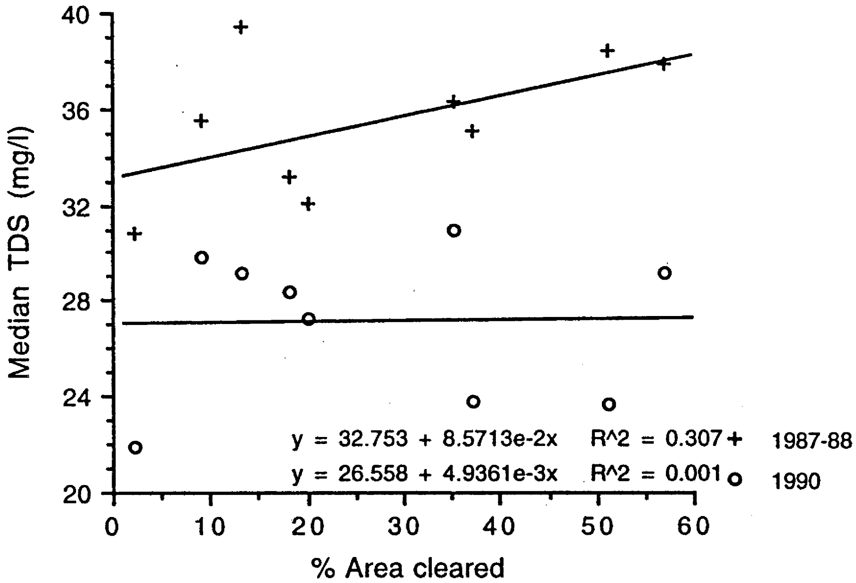

Fig. 3.11.7
Relationship of land use as proportion of catchment cleared to stream conductivity for Sites 10 - 18 (1987-1988; n = 58; 1990; n = 18).

The inherent variability of natural catchments, discussed in Chapter 3.8.4, is an important consideration here. Median solute concentrations at the six sites of minimal inter-catchment variability in the 'montane granite' terrain class in the Tully catchment ranged from 26.8 to 35.1 mg.l^{-1}. By comparison those for the nine Banyan Creek sites ranged from 29.1 to 38.1 mg.l^{-1}, a range only 12 % greater. The intercatchment variability in TDS in the Banyan catchment may be due entirely to the inherent spatial variability of catchment denudation processes. By contrast, the median SSC for sites in Banyan Creek ranges from 2.2 to 14.8 mg.l^{-1}, a range nearly 500 % greater than in observations from the similar montane granitic catchments.

As in the case of SSCs, the solute concentrations of Banyan catchment streams are strongly correlated with streamflow (Fig. 3.11.8). At all sites the relationship between TDS and Q is significant ($p \leq 0.05$) and negative. The values of 'R^2' for TDS in relation to Q are given in Table 3.11.8.

In this data set the non-linearity of the log-transformed data is again apparent. In each case as discharge increases there is a tendency for TDS to decline to a limit, probably about 13 mg.l^{-1}, the mean minimum for the nine Banyan catchment sites (s.d. = 1.5) This value is similar to the minimum TDS recorded in the Tully River during the March, 1990 flood.

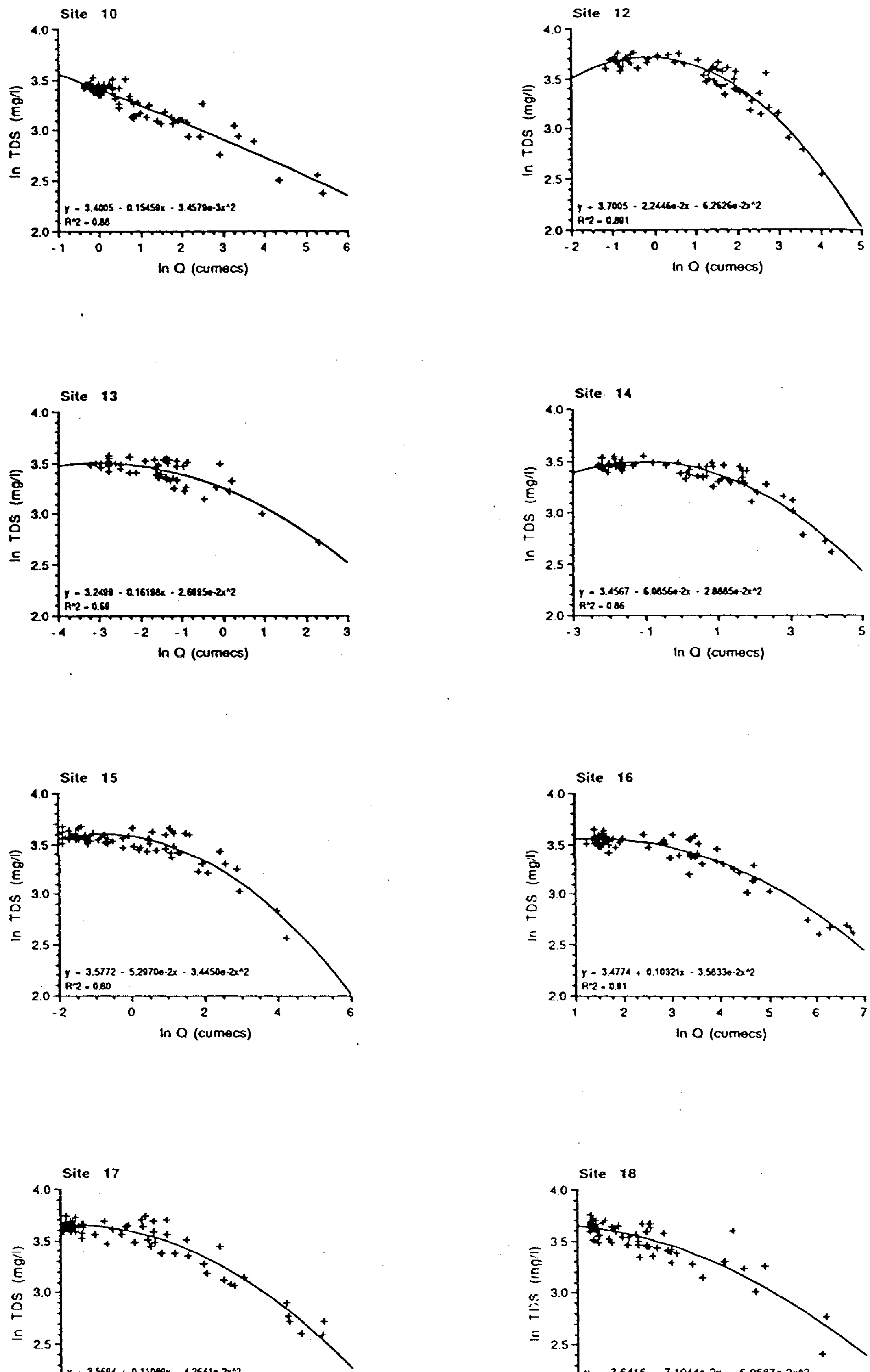

Fig. 3.11.8
Solute rating curves for Banyan Creek sub-catchments.

Site	n	*ln* TDS v *ln*Q (linear)	*ln* TDS v *ln* Q (2nd order polynomial)
10	76	0.880	0.881
12	74	0.671	0.891
13	53	0.566	0.691
14	70	0.604	0.863
15	76	0.542	0.826
16	75	0.805	0.914
17	75	0.800	0.917
18	69	0.735	0.779

Table 3.11.8
Correlation between streamflow and TDS for Banyan Creek subcatchments.

This concentration must be limited by the solute concentration in precipitation which effectively fixes the lower end of the TDS range. The upper end, on the other hand, is likely to be most affected by catchment characteristics, with higher TDS expected in catchments with high levels of agricultural land use. Thus the slope of the TDS rating curve would be steeper for these catchments. For the eight stations in the Banyan Ck catchment for which stage data were collected there is a positive relationship, although, as with the SSC data, the relationship is not significant ($p \leq 0.05$).

As illustrated in Fig. 3.11.9, the sediment yield at low discharges is dominated by solutes, whereas at high discharges it is particulate load that represents the bulk of the sediment transported. Sites 10 and 17 (of 31.6 and 65.8 km2 respectively) were chosen to illustrate this comparison as strongly contrasting in land use (1% v 49% cleared), but with reasonably similar catchment areas.

Given a consistent positive correlation between area cleared and particulate concentration and no clear relationship with solute concentration, it would be reasonable to expect a systematic increase in the proportion of sediment load carried in suspension as the cleared area increased. There is some evidence of this pattern in the data (Table 3.11.9), with the exception of Site 13 where an outlying SSC observation dominates the data set. The discharge at which particulate concentration exceeds that of solutes also appears to be influenced by land use effects on sediment entrainment and transport. At Site 10 this occurs at 20 % of maximum Q, whereas at Site 17 it occurs at only 4 % of maximum Q (Fig. 3.11.9). These results suggest that anthropogenic catchment modification must be taken into account in studies comparing the relative efficiency of physical and chemical processes of denudation.

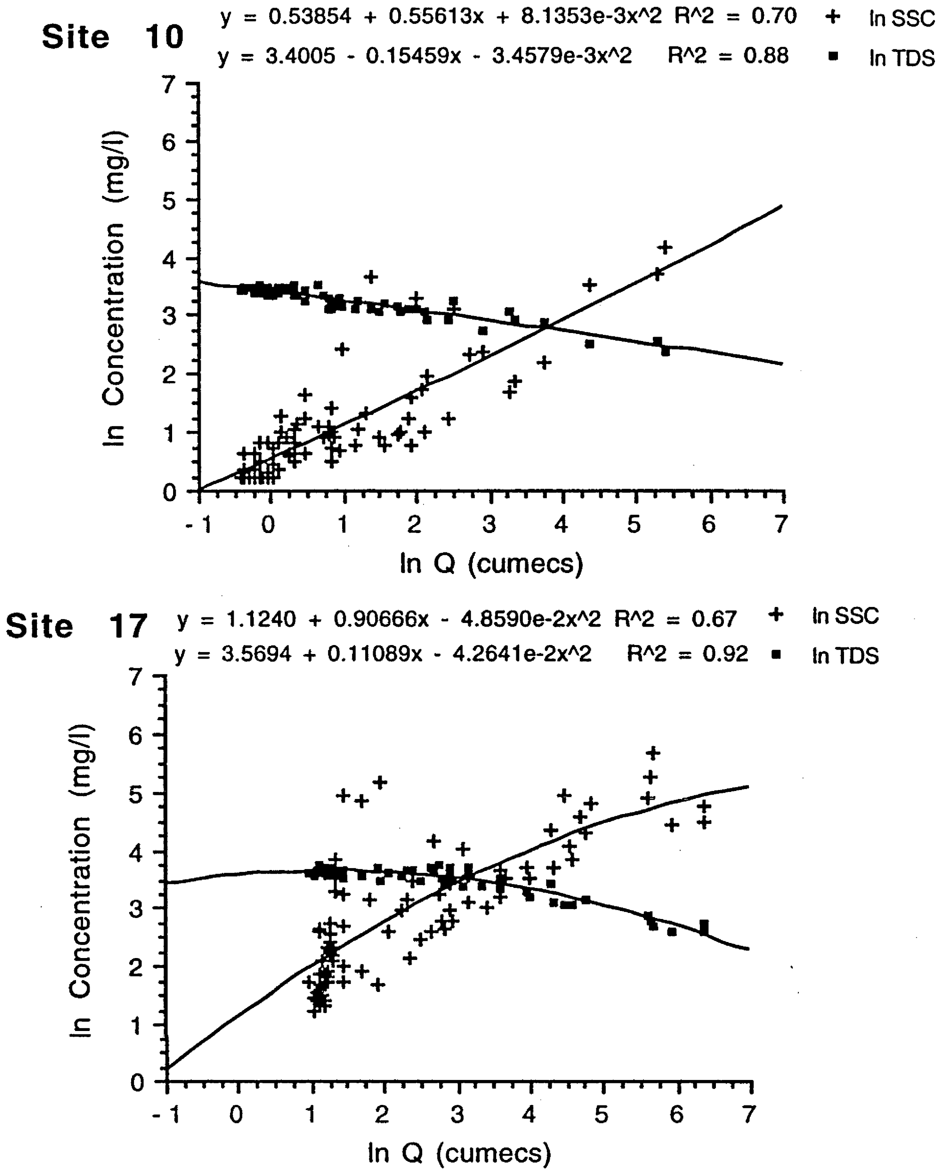

Fig. 3.11.9
Comparison of suspended and dissolved load rating curves for sites with contrasting land use (Site 10 - 1 % cleared; Site 17 - 49 % cleared).

Site	% area cleared	Ratio of suspended to dissolved load
10	1	2.22
12	12	2.88
13	17	7.01
14	19	3.16
15	34	5.89
16	36	4.08
17	49	5.64
18	53	4.20

Table 3.11.9
The ratio of suspended to dissolved load in streams of Banyan Ck. catchment.

The results from the Banyan Creek catchment show that stream suspended sediment concentrations, in catchments with significant areas of sugar cane cultivation, are increased, particularly at high flows. There is little evidence to suggest that solute concentrations in the Banyan Creek catchment have been significantly altered by land use change. The implications of the results reported in this section for long-term sediment yields from the Tully catchment are discussed in Chapter 4.

3.12 *SUMMARY.*

The results presented in Chapter 3.4.1 and 3.4.2 show that good estimates of both the suspended and solute concentrations in the Tully River can be obtained from turbidity and conductivity meters, respectively. These relationships were used to investigate sediment and solute transport in the Tully catchment and spatial variation in those parameters within the catchment during two wet seasons.

Suspended sediment concentrations exhibit clockwise hysteretic behaviour in relation to streamflow, which is the commonly observed pattern. The data suggest that sediment depletion occurs within events, but probably not between events. The combination of Q lagging SSC maxima and within-event sediment depletion means that waters with the highest SSC will enter Rockingham Bay well in advance of the maximum discharge so that mixing and settling could greatly reduce the peak SSCs before there was sufficient outflow to transport them to the offshore islands.

The anti-clockwise hysteresis of the solute concentration is a little unusual, although by no means uncommon. Different components of the solute load exhibit differing patterns of behaviour in relation to streamflow. The relative importance of suspended and dissolved loads appears to change in favour of the suspended load contribution as the proportion of the catchment cleared increases.

Sediment mineralogy was dominated by kaolin, given the documented mineralogy of catchment soils, and was not a suitable tracer of sediment sources. Colorimetric analysis of the suspended sediments showed that, at peak streamflows, about half of the sediment came from in situ montane and colluvial soils, most of which retain a rainforest cover. At low streamflow and SSC most of the sediments are derived from alluvial soils by streambank erosion and subsurface flows.

Spatial distribution of both sediment and solute concentrations in the Tully catchment were investigated with respect to the long profile, Tully River sub-catchment and Banyan Creek sub-catchment patterns. These differing methods of analysis all indicate a significant increase in sediment concentrations with increasing areas of agricultural and pastoral land uses. Although this is clearly the case for agricultural land, implying an increase of about an order of magnitude for a completely cleared catchment, it is much less clear for grazing land for which a relatively small increase, by a factor of about two, is likely. However, there is a high level of variability between catchments of superficially similar characteristics, and the strong association between topography, lithology, soils, and land use makes attribution of clear cause/effect relationships difficult.

The results of the analyses presented in this chapter show that sediment yield in the Tully catchment is quite low by both regional and world standards, but generally consistent with yields from high runoff catchments on granite. The relatively low yields occur in spite of 8 % having been cleared for agricultural and 12 % for pastoral uses. Suggested reasons for the low sediment yield include tectonic stability, low inter-annual rainfall variability, soils of relatively low erodibility and high permeability, the absence of land clearing on steeplands, and the adoption of zero tillage/residue retention cropping practices on about 25 % of the Tully cane lands.

CHAPTER FOUR

SEDIMENT YIELD RESPONSE TO LAND USE CHANGE

CONTENTS

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4.0 General Introduction

This chapter examines the evidence for changed sediment yields in the Tully River catchment in response to land use change, and the magnitude of such changes. Environmental variables which may lead to changed sediment yield are discussed in 4.1, with emphasis on those variables of greatest relevance to the Tully catchment (climate and land use change). The discussion of the effect of land use change on sediment yield concentrates on two themes. Firstly, the perception of the relationship between land use change and land degradation in Australia is examined and secondly, the general characteristics of the relationship between land use change and landscape response are discussed.

Chapter 4.2 provides a brief review of the reported increases in sediment yield in response to changed land use. In Chapter 4.3 an interpretation of the sediment yield response to land use change in the Tully River catchment is made, based on the data presented in Chapter 3, in order to construct a sediment yield history for the catchment. The evidence for channel aggradation in the Tully River is examined in Chapter 4.4.

4.1 CAUSES OF VARIATION IN SEDIMENT YIELD.

4.1.1 Uplift:

Sediment yield rates are increased by tectonic uplift (Yoshikawa, 1974; Adams, 1980) and, in the long term, the denudation rate approximately equals the uplift rate. Although the possibility of minor Holocene uplift is suggested for the highlands of northeast Queensland (Wyatt, 1972), the suggestion is not supported in the more recent review by Willmott and Stephenson (1989). There has been no regional tectonic activity relevant to this study.

4.1.2 Sea level:

Sea level change is not likely to be a significant factor in the Tully catchment at the time scales of relevance to this study. The period of interest is the last century, within a period of stability on the millenial time scale. Sea level fell about 1 m, relative to the Queensland coast, over the last 5-6 ka (Chappell *et al.*, 1983) and a relatively rapid rise of low magnitude on the decadal time scale (Barnett, 1984; Pirazzoli, 1986). Neither the minor Holocene fall nor the smaller recent rise in sea level will have affected catchment sediment yields during the last century. There may have been some minor changes in estuarine morphology and sediment distribution.

4.1.3 Climate:

Sediment yield varies with spatial patterns of climate (Langbein and Schumm, 1958; Jansen and Painter, 1974) and Quaternary climate changes have caused changes in slope denudation, valley alluviation and sediment yield rates in eastern Australia (Butler, 1959; Bowler, 1986) and elsewhere.

Knox (1972), working in the North American mid-west, has suggested that, during shifts in climate (particularly rainfall), the soil, vegetation and climate will not be at equilibrium, and sediment yield will increase until a new equilibrium is reached. Historical evidence from semi-arid areas of the U.S.A. indicates that a climatic shift to greater humidity may result in channel incision but a shift to greater aridity is often followed by hillslope erosion and channel aggradation (Hereford, 1984; Wells and Balling, 1989; Balling and Wells, 1990). In southeastern Australia secular change in rainfall (Kraus, 1955; 1963, Gentilli, 1971, Pittock, 1975; 1983) has caused changes in the area of land degrading by sheet erosion (Pickup, 1976), channel width, hydraulic capacity and bedload in streams of eastern New South Wales (Erskine and Bell, 1982; Warner, 1987; Erskine and Warner, 1988; Nanson and Erskine, 1988). These regions are geomorphically sensitive to climate change. The humid tropics, on the other hand, lie within the relatively insensitive part of the published climate-sediment yield curves and there is no evidence to suggest that such periods of geomorphic disequilibrium are of consequence in the humid tropics.

Secular changes in rainfall erosivity, on the other hand, are likely to result in changes in sediment yield irrespective of the climatic regime. The erosivity of rainfall is related to both the energy of rainfall impact and the rainfall intensity. Energy is determined by the quantity of rainfall and its intensity. Rainfall intensity is, therefore, a major determinant of erosivity. Studies of temporal variation in rainfall have been dominated by analysis of annual or monthly rainfall totals rather than fluctuations in intensity which assume much greater importance when examining climate variability in relation to geomorphic response. An increase in, principally summer, precipitation in New South Wales and its likely association with an increase in the frequency or intensity of storm-type rainfall events was suggested by Cornish (1977) to be a likely cause of increased gully, sheet and stream bank erosion. The possibility of significant changes in gully erosion rates as a result of greater frequency of high intensity rainfall since 1950 in eastern New South Wales has been suggested by Graham (1984). These workers have assumed that the relationship between rainfall total and rainfall intensity is constant over time. However, Neil and Fogarty (1990), Neil & Brierley (1990) and Yu and Neil (1993a, b) have shown that the relationship between total rainfall and rainfall intensity is not constant over time for the Southern Tablelands, northeastern wet tropics and southwestern regions of Australia, respectively. As has been shown in Chapter 2 (Fig. 2.1.14), marked changes in rainfall erosivity occur at Tully which are not consistent with the annual rainfall series (Fig. 2.1.8).

The relationship of high erosivity rainfalls to the annual cropping cycle is also of importance in determining soil erosion and sediment yield rates. Mullins *et al.* (1984) have emphasised this factor with respect to the sugar canelands of northeastern Queensland. They note that an early harvest (eg. July) could result in a reduction of soil loss by 25 % compared with a late harvest (eg. October) because the early harvest allows adequate foliage cover to develop before the onset of the wet season. Subsequent work showed that with a "green cane trash blanket" treatment, full canopy cover was not reached until February-March, regardless of whether harvesting took place in July or November (Prove *et al.*, 1986). Similarly, an "early wet" is likely to result in high erosion rates because of poor ground cover by the crop early in the season. A "late wet", on the other hand, results in lower erosion rates due to the dense foliage cover of the mature sugar cane crop.

4.1.4 Fire:

Although there are studies in which no increase in soil erosion or stream sediment concentrations was observed subsequent to fire (eg. Craig, 1968, cited in Humphreys and Craig, 1981) most studies indicate that increased runoff, erosion and stream sediment concentrations are the usual responses to fires (Ahlgren and Ahlgren, 1960). Several studies (Brown, 1972; Burgess *et al.*, 1981; Wells, 1981; Megahan, 1987) have shown a marked increase in sediment yield (up to a thousandfold) subsequent to burning, with changes in sediment composition occurring. Blong *et al.* (1982) suggested that leaves constituted a high proportion of the sediment initially, but their supply was rapidly depleted, followed by charcoal depletion. High intensity fires have much greater erosion and sediment yield consequences than do low intensity fires (Humphreys and Craig, 1981), and the season of burning can strongly influence the erosion potential and the botanical composition subsequent to fire (Cheruiyot, *et al.*, 1986; Garza and Blackburn, 1985).

In rainforest environments, fire is relatively infrequent and poorly fire-adapted forest communities rely for survival on fuel and micro-climate characteristics which reduce fire intensities to extinction at their boundaries (Stocker and Mott, 1981). When fires do occur, eucalypts (in Australia) will often invade the disturbed area. Although understorey colonisation by rainforest species may eventually result in re-establishment of a mature rainforest, during the eucalypt phase the forest is likely to be much more susceptible to fire. This pattern is generally similar to that which can occur after rainforest disturbance by cyclonic winds. In fact, the post-cyclone eucalypt phase is also a period of enhanced fire hazard because of both increased fuel loads and changed micro-climate within the forest. In the northeast Queensland rainforests in areas of mean annual rainfall > 2 500 mm there is some evidence of cyclone-fire interaction. However, it is most pronounced in areas of lower rainfall (Webb, 1958).

That fires do occur in high-rainfall rainforest catchments in the study area is demonstrated by the occurrence of a fire in the catchment above Site 10 on 26.11.1987, before the onset of that summer's wet season (The wildfire register of the Queensland Forest Service contains no data on this fire). This area was under the approximate southern boundary (Walker and Reardon, 1986) of the eye of Cyclone Winifred (1.2.1986) and it is likely that the post-disturbance state of the vegetation had some influence on its susceptibility to fire. The mean SSC in the post fire period (48 days) was about 15 % greater than during the pre-fire period (27 days), despite mean stream stage being about 20 % lower in the later period. The data available are inadequate to make any generalisations about the effect of rainforest fires on sediment yields from the Tully catchment.

Prior to 1942 virtually all cane cut in the Tully District was cut green. Cane firing was used to remove "trash" from the cane crop prior to harvesting and, particularly during the era of manual cane-cutting, to remove vermin (snakes etc.), for health reasons and because it was cheaper to cut after burning (Jones, 1961; 357). More recently, green cane cutting and trash retention has become a more common management practice (see Chapter 2). In this study, the progress of cane firing within individual subcatchments was not monitored, but was accepted as a normal component of the sugar cane-growing landuse. Current trends in cane harvesting practice being toward green cane (unburnt) harvesting means that it is likely that some decline in both sediment and nutrient concentrations has occurred. In the absence of data it is not possible to quantify this effect.

4.1.5 Land use change:

Sedimentological evidence indicates a correlation between land use change and valley alluviation caused by accelerated hillslope erosion. Examples include the Neolithic or possibly earlier in southern England (Burrin, 1985), the late Bronze Age and early Iron Age in central England (Brown and Barber, 1985), and at about 1 000 - 700 BP in southern Sweden (Dearing *et al.*, 1987).

In the Southern Hemisphere, Hamilton *et al.* (1986) report an erosion response to forest clearance from at least 4 800 BP in southwest Uganda, McGlone (1983) and Hughes and Hope (1979) describe erosional consequences of Polynesian forest firing and clearance in New Zealand (800 - 600 BP) and Fiji (> 1 000 BP) respectively, and the erosional consequences of pre-Incan agricultural activity are evident in 1 400 and 1 100 BP dust layers in ice cores from the Quelccaya ice cap in southern Peru (Thompson *et al.*, 1988). Gillieson (1985) and Spencely and Alley (1986) report marked increase in erosion rates from about 9 000 BP and during the last few centuries, respectively, in the New Guinea highlands.

Traditional wisdom holds that the early Australian settlers were unable to perceive the changes in the landscape which were occurring as a result of land use change. This lack of perception is attributed to their unfamiliarity with the particular characteristics of the Australian landscape, which differed markedly from that of Great Britain, and to the subtleties of the changes. However, there is historical evidence that there was an awareness of the potential for land degradation from early in Australia's settlement. Land degradation, in the form of soil fertility decline, was reported by Collins (1804: 273) as early as 1798. The drought of February, 1799 led to ponds becoming "..brackish, and scarcely drinkable. From this circumstance, it was conjectured that the earth contained a large portion of salt; for the ponds even on the high ground were not fresh." (Collins, 1804: 408). Robertson (1853) describes drainage lines in western Victoria which were rarely entrenched and carried a good cover of perennial tussock grass. Within ten years of settlement, in about 1841, overgrazing had resulted in perennial grasses being replaced by annual species, soil exposure, saline runoff and gully incision to 3 m deep. While prospecting the Southern Tablelands for gold on behalf of the New South Wales government in October, 1851, W.B. Clarke observed that "... the deepest injury that could be inflicted...would be the introduction of the system of swamp drainage which obtains amongst the agriculturalists of Europe. ... I do not know what this beautiful and well-watered country would do if any attempt should be made to drain the swamps and boggy places which so often occur..." (Clarke, 1860; p. 27). Wind erosion was also strongly in evidence at this time. Darwin (1845, p. 418) reports (20.1.1836; east of Bathurst) the "... sirocco-like wind of Australia ... Clouds of dust were travelling in every direction; and the wind felt as if it had passed over a fire."

Mitchell (1991) has examined the question of perception of land degradation in colonial Australia in some detail. He cites the writings of Sturt (1833; p. 9), Mitchell (1848; p. 9 and 12), Trollope (1873; p. 330), Dixon (1892; p. 202) and Millen (1899; p. 4) as clear evidence that there was an awareness of the role of land use change as an agent of land degradation in Australia soon after settlement.

Although none of these works refer specifically to the sediment yield consequences of land use change, many refer to changes in ground cover which must have had soil erosion and sediment yield consequences. For example, Sturt (1833;p. 9) states that "...the ground on both sides of the [Macquarie] river looked bare and arid" due to overgrazing by cattle, Mitchell (1848; p. 9) refers to overgrazing by sheep to the extent that "...not a blade of grass could be seen...", and Trollope (1873; p. 330) noted that "...salt-bush was disappearing on runs which had carried sheep for many years, ...it certainly receded as the squatters advanced ... [and,] ... though it [salt country] seems to be as bare as a board, sheep will keep their condition...". Clearly, land use change in earliest colonial Australia brought about changes recognised as capable of increasing erosion and sediment yield rates. More recent studies have quantified the magnitude of these changes and clarified the temporal sequence of catchment response.

4.2 RESPONSE OF SEDIMENT YIELD TO LAND USE CHANGE:

Many attempts have been made to relate rates of sediment yield to the climatic characteristics of catchments (eg. Langbein and Schumm, 1958; Fournier, 1960; Wilson, 1973) on a global scale. However, the available data did not permit a detailed quantification of the role of land use, although, within a given region, this was considered to be the primary determinant of sediment yield (Wilson, 1973; Douglas, 1967a). In this section a brief review is given of the sediment yield response to land use change in temperate (with emphasis on southeastern Australia) and tropical (emphasis on northeastern Australia) environments. The pattern which emerges from the Tully catchment analyses can then be seen in the context of results from elsewhere in eastern Australia in a range of different environments.

4.2.1 Temperate environments:

Results of studies in southeastern Australia provide examples of the sediment yield response to land use change in a temperate climate. The 'natural' sediment yields reported are generally ≤ 3.0 $m^3.km^{-2}.yr^{-1}$. Douglas (1966) reported a denudation rate of 3 $m^3.km^{-2}.yr^{-1}$ using stream load data from a relatively undisturbed catchment, Prosser (1989) reported a rate between 1.0 and 1.7 $m^3.km^{-2}.yr^{-1}$ as the mean for a period of about 3 000 years using sedimentation rates, and Neil and Fogarty (1991) estimated a rate of 2.8 ± 0.7 $m^3.km^{-2}.yr^{-1}$ from sedimentation rates in small farm ponds over a period of 15 years. Edwards (1988) reports a rate of 4 $t.km^{-2}.yr^{-1}$ measured on plots of undisturbed grassland in central New South Wales.

Rates for pasture are about an order of magnitude greater than the background rates. Edwards' (1988) plot data indicate a mean rate of erosion on moderately disturbed pastures of 21 $t.km^{-2}.yr^{-1}$, and on sown pastures of 43 $t.km^{-2}.yr^{-1}$. Costin (1980) recorded a mean sediment yield of 18 $t.km^{-2}.yr^{-1}$ on a moderately heavily grazed catchment near Canberra. Farm pond sedimentation studies (Neil and Galloway, 1989; Neil and Fogarty, 1991) showed that sediment yields from native pasture, 'improved' (sown) pasture, heavily overgrazed pasture and under cultivation were all markedly higher than those from native forests (Table 4.2.1).

The high sediment yields in pine plantation catchments (Table 4.2.1) are attributed to forest roading (Neil and Galloway, in prep.), a result consistent with other work investigating the sources of sediment in logged forests (eg. Brown and Krygier, 1971; Megahan and Kidd, 1972)).

Land use	Class mean ($m^3.km^{-2}.yr^{-1}$)	Increase above natural rate ($2.8 \pm 0.7\ m^3.km^{-2}.yr^{-1}$)
Native pasture	10.7 ± 6.5	x 3.8
Improved pasture	15 ± 3.5	x 5.4
Crops	58 ± 31	x 21
Overgrazed pasture	76 ± 30	x 27
Pine plantation	93 ± 47	x 33
Discontinuous gullies	31 ± 11	x 11
Continuous gullies	179 ± 231	x 64
Seepage scald	900	x 320

Table 4.2.1
Increase in sediment yield attributed to land use change from small catchments on the Southern Tablelands, NSW (from Neil and Fogarty, 1991).

The sediment yield increase due to changed land cover ranges from 4 times (native pasture) to 33 times (pine plantations) that under native forest.

The effect of land use changes resulting in the formation of new landforms, such as gullies and seepage scalds (due to dryland salinisation), is much greater. Discontinuous gullies, where significant deposition occurred within the gully system, had sediment yields similar to improved pasture or cropland. Continuous gullies, on the other hand, had sediment yields which averaged more than 60 times the natural rate and the yield from the only seepage scald investigated was about 300 times the background rate (Neil and Richardson (1990). In summary, these results indicate an increase within an order of magnitude for grazing lands, and about an order of magnitude for cultivated and overgrazed lands.

Neil and Fogarty (1991) emphasised the differences in sediment yields when land use change results in changed landforms (eg. gullies, seepage scalds) rather than simply changing land cover, and also discussed the contrasting temporal patterns of sediment yield for differing effects of land use change. For example, sediment yields due to sheet erosion are likely to be governed by the combination of climate and management in a given season. On the other hand, gullies which were initiated over 100 years ago may continue to yield large, but declining, quantities of sediment, regardless of current land management. Any lag between land use change and gully initiation is likely to be largely due to a delay until rainfall of sufficient intensity to initiate incision occurs.

In the case of seepage scalds the response is more complex. Land clearing may only result in seepage scald initiation decades later, after a lag while groundwaters gradually rise, and followed by a particular climatic sequence (high rainfall to bring saline groundwaters near the surface; low rainfall to induce evaporative concentration). In areas so affected, ground cover may be degraded by exposure to saline soil water and catastrophic soil erosion and sediment yield may ensue (Bullock and Neil, 1990).

By comparison with erosion rates resulting from changes in land cover, the development of a new landform as a result of land use change, such as a gully or a seepage scald, is likely to result in relatively large sediment yields. Catchments where sediment yield is dominated by land use change initiated new landform development are also likely to exhibit quite different temporal patterns of sediment yield.

4.2.3 Humid tropical environments:

The wet tropics landscape of northeast Queensland is regarded as a geomorphically stable environment with quite low sediment yield and erosion rates, while under the natural rainforest cover (Capelin and Prove, 1983). The results of Gilmour (1977) and Gilmour *et al.*, (1980) are cited as an example of this stability, with an erosion rate of about 400 - 500 t.km^{-2}.yr^{-1} calculated from the North Creek catchment on metasediments east of Babinda and 80 km north of Tully. However, this rate is about 100 times the "natural" rate on the Southern Tablelands (Neil and Fogarty, 1991), which is surprising given a tectonically stable catchment under rainforest cover, albeit in relatively steep terrain. Douglas (1967a) reports sediment yields generally in the range 5 to 50 t.km^{-2}.yr^{-1} (assuming bulk density = 2.6) from granitic and basalt catchments in northeast Queensland.

Changes in land use in the North Creek catchment resulted in an increase in peak SSC from 180 mg.L^{-1} before logging, to 520 mg.L^{-1} in the two years after logging and to 4 000 mg.L^{-1} subsequent to clearing (Gilmour *et al.*, 1982). Capelin and Prove (1983) estimated that these changes in sediment concentration due to land use change represented increases from 480 t.km^{-2}.yr^{-1} to 1 090 t.km^{-2}.yr^{-1} (logging) and to 5 960 t.km^{-2}.yr^{-1} after clearing.

Prove (1991) found that average soil loss was 15 000 t.km^{-2}.yr^{-1}, ranging from 7 000 to 50 000 t.km^{-2}.yr^{-1}, under sugar cane cropping on krasnozem soils and Matthews and Makepeace (1981) report soil loss of 38 200 $t.km^{-2}$ in the course of a single wet season from krasnozem soils on a 16 % slope. Mullins *et al.* (1984) calculated soil loss of 38 400 $t.km^{-2}.yr^{-1}$ for podzolic soils with a 12 % slope using the USLE. Of course only a fraction of the eroded soil, as determined by erosion plot trials, will become sediment yield from the catchment. The fraction varies with catchment characteristics (eg. Roehl, 1962). Prove and Hicks (1991; citing Arakel *et al.*, 1989) suggest that about 80 % of soil eroded is estimated to remain in the paddock. However, although Arakel *et al.* (1989) suggest that about 20 % is aggraded in stream channels, it is unclear from their results what percentage remains in the paddock and what percentage is transported through the channel network and offshore.

Chorley, Schumm and Sugden (1984; citing the results of Douglas (1969)) report sediment yield increases of between 2 and 17 times for the transition from forest to cultivation in a variety of wet tropical catchments, consistent with Pearce' (1990; pers. comm.) suggestion that an order of magnitude increase in soil loss is likely with land use change from forest to agriculture.

The very high runoff coefficients in the wet tropics (ranging from 59 % to 89 % for the 6 catchments reported by Bonell, *et al.*, 1986), in association with very high rainfalls, results in much lower SSC per unit mass/volume of soil lost, by comparison with drier areas with lower runoff coefficients. In the context of both coral growth response to land use change and of detrital inclusions in corals as recorders of land use change, the nature of the relationship between erosion rate and stream suspended sediment concentrations is of considerable importance. A given volume of soil loss from the Tully catchment (runoff coefficient = 74 %) would result in a much lower sediment concentration in river plumes reaching coral reefs than would be the case for the same volume of soil lost from the Herbert catchment (runoff coefficient = 37 %), which, in turn, would be lower than from the Burdekin catchment (runoff coefficient = 12 %; Hausler, 1991).

4.3 *INFERRED RESPONSE OF THE TULLY RIVER CATCHMENT TO LAND USE CHANGE:*

Suspended sediment time series: In the Tully River catchment land use change has resulted in changed land cover, for example for agricultural, pastoral, infrastructure and construction purposes. There is little evidence of new landform development as a result of land use change. The evidence from stream channel cross-section resurveys suggests that no significant channel incision (or aggradation) has taken place and the high rainfall precludes the development of salt scalds. However, clearing of stream banks has led to increased bank erosion rates.

Mass movement debris was observed after torrential rain at a number of steeplands sites in the Tully catchment, and must contribute to some of the water quality variability between subcatchments. With the exception of slope instability due to road construction for access to the Kareeya Power Station, mass movement in the Tully catchment is largely the result of natural processes rather than instability due to land use change.

The following analysis of the sediment yield response to land use change in the Tully River catchment concentrates largely on the response to change in land cover. The analysis assumes a correlation between clearing for agricultural and pastoral purposes and stream bank clearing, an assumption justified qualitatively by examination of the aerial photographs.

Linear regressions of the percentage of sub-catchment cleared against the median sub-catchment SSC and against the % increase in SSC due to land use change were used to determine an appropriate factor of SSC increase (due to land use change) for incorporation into the sediment yield time series. The use of medians makes this estimate somewhat conservative, although the estimates given the most weight in deciding the appropriate factor were derived from the high stream flow 1990 sampling period on the basis that it is such major events which yield the greater part of the sediment load and result in sediment transport to the offshore island fringing reefs.

The estimates of increased SSC were then combined with the land use history of the catchment (Chapter 2) and the known sediment yield for 1990 (Chapter 3) to derive an estimated potential sediment yield time series. The potential sediment yield was converted to an estimate of the actual yield using the time series of rainfall erosivity (Chapter 2).

This approach is somewhat convoluted, and it is worthwhile pointing out why an often used alternative, the Universal Soil Loss Equation (USLE), was not used. In short, the USLE was not used in this study because it is not universal. It has become "..the most widely used and misused predictive measurement of erosion.." and its ease of computation has led to "..gross misuse" (Stocking, 1987: 58). Wischmeier (1976) specifically cautions against its application for catchment erosion estimation, the purpose of this research. Furthermore, extrapolation of the empirically derived USLE from temperate to tropical landscapes is also inappropriate without the support of an adequate local data base. For these reasons, the space-time substitution approach used in this research is considered more appropriate.

<u>Solute time series:</u> Although the relationship between TDS and catchment area cleared in the Tully catchment is significant (Eqn. 3.10.7, 3.10.8 and

3.10.9) the increase in median TDS implied by these equations is in the order of 1.3 - 1.5, and less in the Banyan catchment. By comparison with the change in sediment concentrations, this effect of land use change is insignificant. Unlike the pattern of SSC, downstream increases in TDS, as indicated in Fig. 3.9.3, are probably the result of longer residence times and subsurface flow paths, and a greater proportion of runoff occurring via subsurface flow in floodplain areas than in montane areas. Substantial change in solutes due to land use change is probably limited to relatively low rainfall catchments with saline groundwaters, which is not the case in the wet tropics of northeast Queensland. Consequently, no attempt is made herein to construct a time series of land use related change in solute concentrations.

Data for individual solutes were acquired only during the 1990 sampling period and only for the Tully River at Euramo (Site 1). As a result it is not possible to reconstruct a nutrient flux time series for the Tully River.

4.3.1 Inferred sediment yield response, Banyan Creek catchment data:

4.3.1.1 Regression relationship of median SSC in relation to percentage of catchment cleared:

An estimate of sediment yield response to land use change in the Banyan Creek catchment can be obtained using the regression equations for the relationship between % area cleared and median SSC established in Chapter 3.11. Median SSC with no land clearing is taken to be the intercept value and the regression line is extrapolated to 100 % cleared to obtain an estimate of the effect of totally clearing a catchment. The estimate obtained in this way is for purposes of comparison only, could only be applied to catchments of > 50 % cleared with reservation, and could not be applied to catchments where any significant amount of clearing has taken place on steeplands. These estimates are for conditions such as those in the Tully catchment in which land use change is largely confined to the alluvial plains. Error estimates are calculated from the 95 % confidence interval of the β term in the regression equations. The results of these estimates, from Chapter 3.11, are as follows:

Median SSC = 1.23 + 0.13. % cleared [Eqn. 3.11.2]

(9 sites x 58 observations; 1987-88 data) - implies an increase in median SSC by a factor of about 12 $\pm$ 6 for a catchment 100 % cleared for agriculture.

Median SSC = 2.16 + 0.70. % cleared [Eqn. 3.11.3]

(9 sites x 25 observations; 1990 data) - this equation implies an increase in median SSC by a factor of about 33 $\pm$ 16 for a catchment 100 % cleared for agriculture.

Median SSC = 1.82 + 0.19. % cleared [Eqn. 3.11.1]

(9 sites x 83 observations; 1987-88 and 1990 data) - this equation, using all available data, implies an increase in median SSC by a factor of about 11 $\pm$ 6 for a catchment 100 % cleared for agriculture. Median SSCs at the "control" Site 10 are 1.8, 3.5 and 2.2 for the data sets used in Eqn. 3.11.2, 3.11.3 and 3.11.1, respectively, indicating that the intercept values are realistic.

This approach has a number of obvious limitations. For example, use of medians reduces the contribution of very high SSC values because SSC distributions are strongly skewed. Conversely, sampling was deliberately biased towards high stream flows, at which the highest SSCs generally occur.

Nevertheless, these results are consistent with findings in most environments that land use change (forest to agriculture) is likely to induce an increase in sediment yield by about an order of magnitude. It is important to reiterate that, in this case, land use change is largely confined to the alluvial plain.

4.3.1.2 *Median test to determine percentage increase and confidence intervals of the increase:*

When randomly sampled observations of SSC for streams in a given region over a given time period are plotted in ascending order on log - normal probability paper a consistent pattern may emerge in which the slope of the line connecting the data points for a given stream approximates a straight line for the second and third quartiles of observations, and the line for each set of data points (each stream) approximates the other lines. Outside this range of data points (that is, the first and fourth quartiles) each line may diverge markedly from that for the second and third quartiles, and also diverge from the other lines. This pattern was evident (Neil, unpubl. results) in SSC data from the Snowy Mountains region of southeastern Australia (SMHA, 1970;1971; 1972) It appears that the position of the straight line segment, in relation to the y-axis, is indicative of the modal behaviour of the catchment. Suspended sediment concentrations in the lower quartile are likely to be associated with low stream flows so that their contribution to total load is small and can be largely ignored. Suspended sediment concentrations in the upper quartile are likely to be associated with high stream flows. The product of high stream flow and high SSC means that their contribution to total load is likely to be large. However, it is also likely to be highly variable due, for example, to variation in the extent and intensity of extreme events, and thus not indicative of the normal behaviour of the catchment.

This approach was applied to the Banyan Creek catchment data Chapter 3.11 and the median test (Gibbons, 1971; 131) used to evaluate the significance of the differences and to determine confidence intervals for the analysis.

Table 4.3.1 shows summary results of this analysis for the 1987-88 Banyan Creek data (turbidity is used in these comparisons). Median turbidity in cultivated subcatchments increases, in relation to the reference catchment (Site 10), roughly proportionally to the percentage area cultivated. The results for both the 'urban' and 'construction' sub-catchments (the latter located within the former) indicate a greater increase than catchments which are up to 50 % under sugar cane cultivation. This is in spite of the almost complete absence of unsealed roads within the urban area. Clearly, unsealed roads are a source of high sediment concentration runoff waters, about 100 times that for sealed roads and 1 000 times that for rainforest in the reference catchment. However, they occupy a relatively small area and runoff is of short duration, although the runoff coefficient is c. 1.0.

Site / Land use	n	Increase relative to reference site (10) (Median = 0.6 NTU)	Lower bound of increase	Upper bound of increase
11 (8 % cleared)	58	2.8	2	10
12 (12% cleared)	58	4.2	3.2	15
13 (17 % cleared)	58	2.3	1.8	9.5
14 (19 % cleared)	58	3.0	2.7	13.5
15 (34 % cleared)	58	2.7	2.3	9.5
16 (36 % cleared)	58	5.7	4.3	33.5
17 (50 % cleared)	58	12.7	10.3	53.5
18 (56 % cleared)	58	11.8	10.2	42.5
Urban	43	20	16.3	81
Construction	43	17.7	9.2	119
Sealed roads	8	11.3	1.8	517
Unsealed roads	21	1 100	917	5 225
Banana irrigation runoff	5	2 042	840	3 625

Table 4.3.1
Increase in stream water turbidity in relation to reference site (10) for Banyan catchment sites, and upper and lower bounds for the increase at $\geq$ 95 % CI (1987-88 data).

Banana farm irrigation runoff is responsible for the highest turbidities measured in the Tully catchment. Because irrigation is predominantly carried out during dry periods, the effect of these high turbidities is likely to be limited to low flow conditions. Runoff from banana crops clearly warrants further investigation on three grounds. Firstly, these turbidities are likely to have extremely adverse effects on the ecology of streams which have turbidities 3 orders of magnitude lower under natural conditions. Secondly, these very high turbidities suggest that banana crops may be a more significant source of suspended sediment in the north Queensland wet tropics than previously recognised. Finally, given the rapid expansion in the area of this crop, the very high rates of fertiliser application and the high turbidities, banana crops are likely to have a disproportionately large role in nutrient transport and eutrophication in the region.

A similar comparison can be made using the data from the higher stream flow conditions experienced during the 1990 sampling period (Table 4.3.2). These results suggest that an increase by a factor of about 15 is likely, at flood discharges, for catchments which are about 50 % cleared for agriculture. It is clear that, for these catchments, the increase in wet season turbidities lies between factors of about 5 and 35, with a very low error probability. In two cases only (Sites 11 and 13) the lower bound of the 97.7 % confidence interval is < 1.0, implying that an (insignificant) decrease in stream sediment loads is possible at this level.

The results of this analysis are generally consistent with those for the wet season stream loads using the regression method (above).

Site / Land use	n	Increase relative to reference site (10) (Median = 3.5 NTU)	Lower bound of increase	Upper bound of increase
11 (8 % cleared)	25	3.1	0.95	10.8
12 (12 % cleared)	25	4.5	1.8	10.8
13 (17 % cleared)	25	2.3	0.9	7.5
14 (19 % cleared)	25	6.2	2.5	17.1
15 (34 % cleared)	25	6.7	2.4	25.6
16 (36 % cleared)	25	14.8	5.6	36.4
17 (50 % cleared)	25	17.2	6.7	45.7
18 (56 % cleared)	25	11.6	2.6	26.4

Table 4.3.2
Increase in stream water turbidity in relation to reference site (10) for Banyan catchment sites, and upper and lower bounds for the increase at $\geq$ 95 % CI (1990 data).

The results presented in Tables 4.3.1 and 4.3.2 suggest the following relationships between the % increase and the % of a subcatchment cleared for cultivation:

1987-88 data- % increase = 0.141 $\pm$ 0.032. % cleared (n=8;$p \leq 0.012$) [Eqn. 4.3.1]

1990 data- % increase = 0.280 $\pm$ 0.035. % cleared (n=8;$p \leq 0.01$) [Eqn. 4.3.2]

4.3.2 Inferred sediment yield response,Tully River catchment data:

In a similar manner to that used for the Banyan Creek data, an estimate of sediment yield response to land use change in the Tully catchment can be obtained using the regression relationships between % area cleared and median SSC developed in Chapter 3.10. The following results are obtained:

Median SSC = 2.442 + 0.090. % cleared (Eqn. 3.10.6; 15 sites x 15 observations; 1987-88 data; catchments cleared for cultivation only) - implies an increase in median SSC by a factor of about 4.7 $\pm$ 1.6 for a subcatchment 100 % cleared for cultivation.

Median SSC = 3.581 + 0.079. % cleared (Eqn. 3.10.3; 49 sites x 15 observations; 1987-88 data; all subcatchments) - this equation implies an increase in median SSC by a factor of about 3.2 for a 100 % cleared (for pasture or cultivation) subcatchment. The lower slope coefficient and lower increase factor imply a lower increase factor for grazing lands than cultivated lands, although there are no data which indicate clearly what that factor might be.

The effect of land use change can also be tested by comparing Site 2 (AMTD (Adopted Middle Thread Distance) = 57 km; catchment area = 605 km^2) above which only 9.2 km^2 (1.5 %) is cleared, almost entirely for grazing purposes, with Site 1 (AMTD = 17.5 km), upstream of which about 8 % is cleared for agriculture and 12 % cleared for improved pasture. At high stream flows (that is > 500 cumecs at Site 1), SSC at Site 1 exceeds that at Site 2 by a factor of about 4, the difference increasing slightly as the stream flow increases. Douglas (1967b) compared upper and lower sampling sites in three regional streams and found increases in sediment load (upper to lower) of 2.4 (Barron R.), 1.5 (Davies Ck.) and 2.0 (Millstream Ck.). These increases were attributed to land use effects on the basis of the greater human activity in the lower catchment relative to the upper, and the fact that, in the absence of human activity, greater sediment loads would have been expected in the upper catchments because they are steeper and have higher rainfall. The greater increase factor in the Tully catchment can, at least in part, be attributed to its being calculated on suspended sediment concentration rather than on sediment load.

4.3.3 Reconstruction of Tully River sediment yields:

A simple model of changing sediment yield over time in the Tully catchment has the following form:

$$SSC_t = f(\text{land use, land management practice, rainfall erosivity})_t$$

The analyses presented in the preceding discussions indicate that the overall increase in SSC in the Banyan Creek catchment (indexed to 100% land use change) is by a factor of about 15. In the Tully catchment, on the other hand, it is about 5 times. The difference is attributed to the much higher proportion of the Banyan Ck catchment in high soil erodibility classes than is the case for the Tully catchment (Fig. 2.1.7) and the fact that spatial variability data are only available for the Tully for the 1987-88 sampling period during which the estimated increase in SSC due to land use was probably only a third of that for the 1990 sampling period (by analogy with the Banyan Creek data). However, because the high magnitude events are those which transport most sediment and which have sufficient discharge to reach the offshore fringing reefs, it is appropriate to use a factor which relates to these events. Assuming, as indicated by the foregoing analyses, that the SSC increase indexed to 100% land use change for low frequency/high magnitude events such as the 1990 flood is about 30 in the Banyan catchment (Eqns. 3.11.3 and 4.3.2), and that the lower sediment delivery ratio and flatter terrain of the Tully catchment reduces this by about 66 %, an increase factor of about 10 could be assumed relevant for cultivated lands (eg. sugar cane, bananas). However, given the fourfold increase in SSC between Site 2 and Site 1 (Chapter 4.3.2), an absolute value not indexed to 100% land use change, a factor of 10 appears to be an underestimate, and 15 seems more appropriate. The error estimates calculated in the previous section can be applied to this figure to give an estimate of 15 ± 7.

The appropriate increase factor is less clear with respect to pasture lands. Evaluation of the results of this study suggests that a factor of 2 is probably realistic, although the factor for cultivated land (x15) is adopted for pasture land in the year of clearing. Only improved pasture is included in this analysis. The small area of native pasture on flat terrain is assumed to yield only "natural" sediment loads. There is little evidence of intense storms causing severe soil erosion from well managed pasture on the wet tropical coast of northeast Queensland (Bonell, 1988).

The conversion from SSC data as factors of increase, which are not standardised for catchment area, to sediment yield data, which are defined as yield per unit area, is problematical. In this study it is justified on the following grounds. Firstly, as stated in Chapter 3.10 and 3.11 respectively, there is no significant relationship between catchment area and SSC in subcatchments of either the Tully or the Banyan Creek catchments, and catchment area does not contribute significantly to multi-variate relationships between SSC and catchment characteristics in those data sets. Secondly, contrasting the results of variation within the Banyan catchment, within the Tully catchment and along the Tully main stream has allowed some adjustments to be made to the final sediment yield increase factors which take account of the difference of about an order of magnitude between the area of the largest subcatchments sampled and the Tully catchment itself.

Calculation of the sediment yield time series is as follows:

$SYI(L)_i = 1-(C_i + P_i) + C_i.15 + Pc_i.15 + Pg_i.2$,

where

SYI_i = is an index of sediment yield for the year i, in which a 'natural' catchment has $SYI = 1$,

C = the proportion of the catchment under cultivation,

P = the proportion of the catchment under improved pasture,

Pc = the proportion of the catchment cleared for pasture in the year i,

Pg = the proportion of the catchment under established pasture in the year i, and

L denotes that the sediment yield index is calculated in relation to the land use factor.

and,

$SY(L)_i = SYI(L)_i.\ (A_{i*}/SYI(L)_{i*})$,

where

$SY(L)_i$ = estimated sediment yield ($t.km^{-2}.yr^{-1}$) in the year i,

A_{i*} = the known sediment yield for a given year i*,

$SYI(L)_{i*}$ = the sediment yield index for the given year i*.

The known sediment yield for a given year, the parameter A_{i*}, is that calculated for 1990 for which a specific yield of 71 $t.km^{-2}$ was estimated (Chapter 3.7). Specific sediment yields for all other years are standardised against this estimate.

The most significant features of the resulting sediment yield time series (land use factors only, dashed line in Fig. 4.3.1) are the increase at the commencement of sugar cane cultivation in the mid-1920s, the marked increase associated with clearing for improved pasture in the early 1960s and the increase in sugar cane production in the late 1970s.

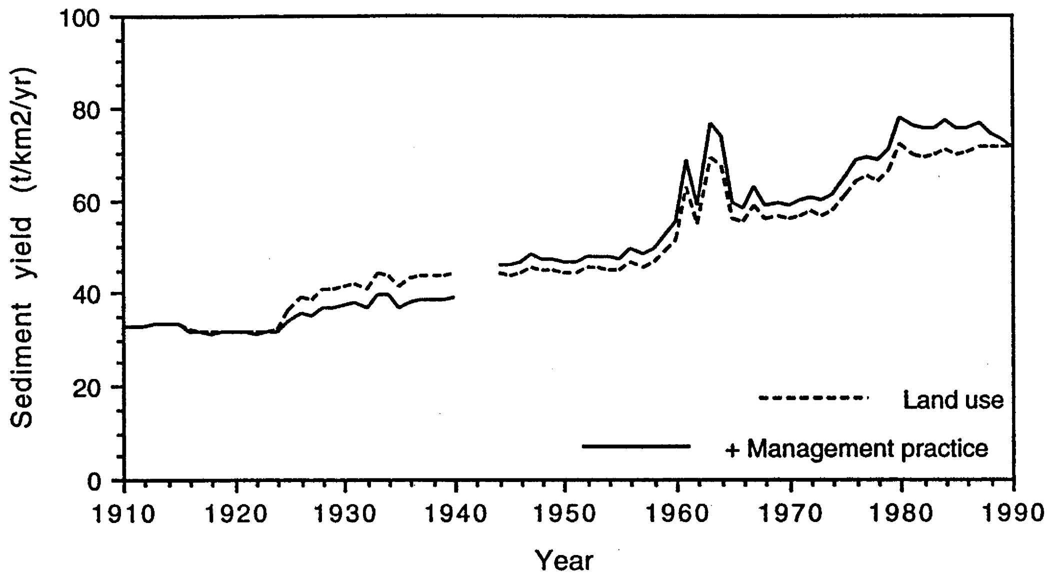


Fig. 4.3.1
Inferred sediment yield response to landuse change in the Tully River catchment indexed to 1990 sediment yield.

Changing land management practices, particularly with respect to sugar cane cultivation, are likely to have influenced the potential sediment yield of the Tully catchment. Results reported by Prove and Hicks (1991) indicate about an order of magnitude decrease in soil loss due to conservation farming practices (Fig. 2.3.4). However, because sediment delivery ratios are likely to decrease with increasing erosion rates, as indicated by the changing particle size distributions (to finer) with adoption of conservation practices (Prove and Hicks, 1991), because the Tully canelands are generally on very flat terrain, and because not all cane growers will apply the maximum level of soil conservation, stream sediment loads from canelands with soil conservation practices applied will not be an order of magnitude less than those without conservation practices. It is assumed herein that sediment yield, as distinct from soil erosion, from canelands without conservation practices will be double that of treated lands. Using the pattern of adoption of these practices outlined in Fig. 2.3.4, an appropriate adjustment to the Tully River sediment yield index can be made. The "trashing" management practices normal before the 1940s are assumed to be the equivalent of modern green cane harvesting practices.

Calculation of the sediment yield time series, adjusted for the effects of changing management practices, is by the same approach as for land use change alone, but with separation of the cultivated lands with and without soil conservation practices:

$$SYI(LM)_i = 1-(C_i + P_i) + Cc_i.9.25 + Cnc_i.18.5 + Pc_i.15 + Pg_i.2 \qquad \text{[Eqn. 4.3.3]}$$

where

SYI_i = is an index of sediment yield for the year i, in which a 'natural' catchment has SYI = 1,

C = the proportion of the catchment under cultivation,

Cc = the proportion of the catchment under cultivation with soil conservation practices,

Cnc = the proportion of the catchment under cultivation with no soil conservation practices,

P = the proportion of the catchment under improved pasture,

Pc = the proportion of the catchment cleared for pasture in the year i, and

Pg = the proportion of the catchment under established pasture in the year i,

LM denotes that both the land use and management practice factors are included in the calculation, and

X and Y are coefficients such that, firstly, X = 0.5.Y and secondly, given the values of Cc and Cnc for the year 1990, $Cc_i.9.25 + Cnc_i.18.5 = C.15$ for i = 1990.

and,

$$SY(LM)_i = \bar{SYI}(LM)_i.\ (A_{i^*}/SYI(LM)_{i^*}) \qquad \text{[Eqn. 4.3.4]}$$

where

$SY(LM)_i$ = estimated sediment yield ($t.km^{-2}.yr^{-1}$) in the year i,

A_{i^*} = the known sediment yield for a given year i*, in this case 1990,

$SYI(LM)_{i^*}$ = the sediment yield index for the given year i*.

Assumptions of this estimate are:

(i) No soil conservation practices have been applied to crops other than sugar cane.

(ii) Pre-1939 sugar cane harvesting was managed by 'trashing' and the soil conservation consequences of this practice were equivalent to modern green cane harvesting practices.

(iii) Post-1945 sugar cane harvesting was managed by burning, with no soil conservation measures practiced until green cane harvesting was introduced.

(iv) Estimation of the area of green cane harvesting is by interpolation of the data of Prove and Hicks (1991).

The significant features of the sediment yield time series, adjusted for changing management practices (solid line in Fig. 4.3.1), are a relatively small increase in the mid-1920s due to the 'trashing' practice, and increases in the 1940s and 1950s resulting from abandonment of "trashing" as mechanical harvesting was adopted, and during the 1970s as the area of sugar cultivation was expanded without the adoption of conservation farming practices. A slight decline is apparent during the 1980s as conservation farming practices have increasingly been adopted.

The Tully River sediment yield, for conditions prior to land clearing and settlement, is estimated at about 30 $t.km^{-2}.yr^{-1}$, based on Eqn. 4.3.3 and 4.3.4. During the period 1920 -1930 SY is estimated at 38 $\pm$ 1 $t.km^{-2}.yr^{-1}$, for 1950 - 1960 at 50 $\pm$ 3 $t.km^{-2}.yr^{-1}$, and during the major clearing phase of 1961 - 1965 at 67 $\pm$ 8 $t.km^{-2}.yr^{-1}$. Completion of this clearing phase led to a reduced SY (1966 - 1975) of 60 $\pm$ 2 $t.km^{-2}.yr^{-1}$, with a subsequent steady increase to about 77 $t.km^{-2}.yr^{-1}$ by 1980. During the 1980s SY is estimated at 75 $\pm$ 2 $t.km^{-2}.yr^{-1}$, although with a decreasing trend as previously noted. The overall increase in sediment yield is by about 240 %, reasonably consistent with the fourfold increase between Site 2 and Site 1 previously referred to.

It is important to note that both the base level sediment yield rate inferred for the Tully catchment and the increase due to land use change (to pasture and to cultivation) are considerably lower than those reported elsewhere in the region (eg. Capelin and Prove, 1983; Prove and Hicks, 1991), although the 'natural' rate is again quite similar to those reported by Douglas (1973).

Limitations of the sediment yield reconstruction include the following:-

(i) The SY increase factors used are estimates only. However, the complexities of the sediment yield response to changing land use, particularly in the context of climatic variability, means that a "best-guess" estimate is generally all that can be achieved.

(ii) The effect of changing land management practices on in-stream sediment concentrations, as distinct from erosion plot results, is largely unknown.

(iii) The sediment yield implications of changed stocking rates on wet tropical pastures is unknown.

(iv) The sediment yield effects of unsealed roads are not explicitly taken into account. However, the establishment of unsealed road networks as the area of cropland increases means that they are included by default in the estimates of sediment yield increase due to cultivation.

(v) Urbanisation effects are not taken into account. The results confirm that urbanisation has a significant effect on SSC.

(vi) The relative effects of traditional 'trashing' and modern soil conservation practices are unknown.

The sediment yield time series described are estimates only of the potential for erosion and subsequent sediment transport, given the meteorological and hydrological conditions of the 1990 water year. A more accurate index requires the inclusion of some measure of temporal variation in rainfall and/or stream flow. The rainfall erosivity index, as described in Chapter 2.1.2.2, is used as it has some physical relationship to the erosion process and weights the extreme events likely to be responsible for most sediment transport and to transport sediments offshore. The low erosion threshold of 50 $mm.day^{-1}$ is used because the terrain type of most relevance is the cultivated and improved pasture land. As the Tully rainfall record only commenced in mid-1925, the index can only be calculated for the period from and including the 1926 water year.

This estimate of sediment yield is calculated as follows:-

$B_i = SY(LM)_i \cdot EI(50)_i$, and

$SY(EI)_i = B_i \cdot (A_{i*}/B_{i*})$,

where

$SY(EI)_i$ = is estimated sediment yield ($t.km^{-2}.yr^{-1}$) in the year i, adjusted for rainfall erosivity,

$EI(50)_i$ = is the rainfall erosivity index (daily threshold = 50 mm) for the year i,

A_{i*} = is the known sediment yield for a given year i*, in this case 1990, and

B_{i*} = is the product of sediment yield and erosion index for the given year i*.

A very different temporal pattern of sediment yield is evident when variation in rainfall erosivity is taken into account in the model (Fig. 4.3.2). The generally higher rainfall erosivity in the period prior to 1955 (Fig. 2.1.14) tends to offset the relatively low impact of land use and management during this period. The late 1960s and 1970s were a period of moderate rainfall erosivity and high erosion susceptibility with a high sediment yield index the result. During the 1980s, the combination of gradually declining erosion susceptibility (Fig. 4.3.1) and low rainfall erosivity (Fig. 2.2.14) have resulted in generally low estimated sediment yields.

Under this scenario, the mean annual sediment yield, for the 62 years with land use data, is 50 $t.km^{-2}$, with a coefficient of variation of 66 %. Estimated sediment yields range from a minimum of 6 $t.km^{-2}.yr^{-1}$ to a maximum of 161 $t.km^{-2}.yr^{-1}$.

This simple model takes account of the factors contributing to soil loss, as defined by the USLE, for example, in the following ways:

R (rainfall factor) - use of the erosivity index based on daily rainfall,

K (soil erodibility factor), L (slope length), S (slope steepness) - assumed constant over time for areas of the catchment, mostly alluvial plain, where land use intensification has occurred,

C (cover) - time series of changing land use, and

P (management practices) - time series of changing tillage and trash management in sugar cane cultivation.

Although such a sediment yield index could not be used to predict soil loss or sediment yield at any specific time or place, it gives an indication of the likely temporal sediment yield patterns for the Tully River since 1926.

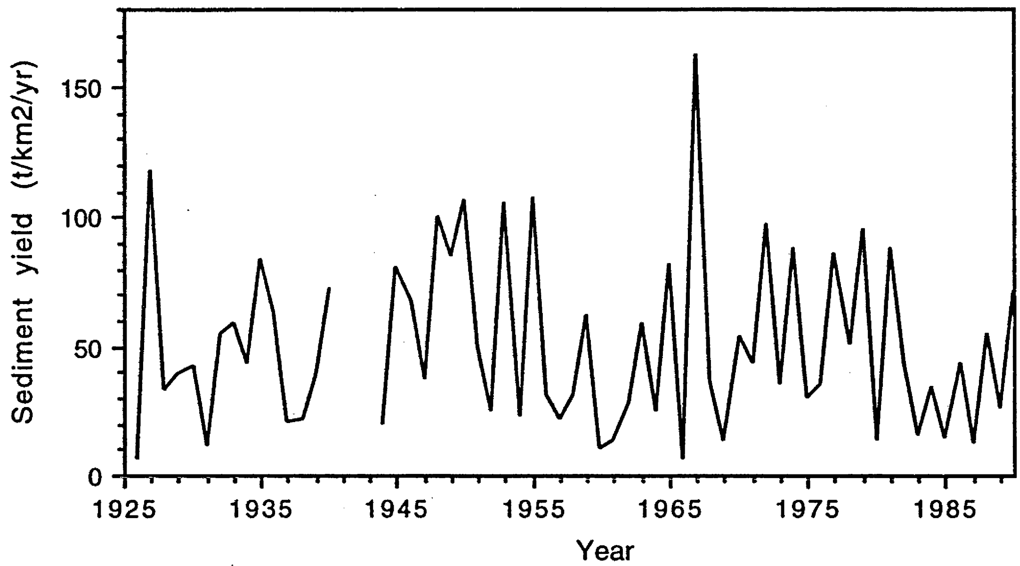


Fig. 4.3.2
Inferred sediment yield response to land use change in the Tully River catchment adjusted for temporal trends in rainfall erosivity.

The sediment yield index, as presented in Fig. 4.3.2, does not incorporate some factors which are likely to influence catchment sediment yields. For example, no account is taken of the effects of forest fires in the catchment. Construction works (eg, Koombooloomba Dam) and the effects of urban development are omitted, as are the effects of unsealed roads on sediment yield. While all of these factors influence stream sediment loads and, with the exception of Koombooloomba Dam, have been shown to do so in this study, it is unlikely that they will alter the general pattern of sediment yield over the last century.

Forest fires are undoubtedly less frequent than under Aboriginal land management regimes and their frequency is likely to be decreasing as a result of greater adoption of green cane harvesting. Cane firing for late harvesting (eg. November and December) may be responsible for forest fires at times of higher rainfall erosivity. The effect of unsealed roads is likely to have increased over time as the network has been extended, in spite of an increase in the length of sealed roads. The effect of urban runoff was probably at its greatest during the 1920s and 1930s as urban expansion in the absence of sealed roads took place. However, the area involved is small.

4.4 CHANNEL AGGRADATION RESPONSE TO LAND USE CHANGE:

4.4.1 Introduction

A further response of sediment yield to land use intensification is sediment aggradation in stream channels. In natural systems, stream channel aggradation is a predicted response to rising sea level, tectonic or isostatic subsidence and periods of climatic aridity. Excess sediment load is deposited when the load:discharge ratio increases (Richards, 1982; p. 53) resulting in aggradation. Given that the increase in sediment yield is generally much greater than the increase in water yield (Richards, 1982; p. 259), increased load:discharge ratios and consequent aggradation are expected as a response to land use change. Channel aggradation in response to changed land use, from natural cover to agriculture, construction, mining, urbanisation and other such uses, is widely documented (eg. Knox, 1977).

In the Tully catchment, Ullman and Nolan (1980) reported that no aggradation had occurred in the Tully River at the Euramo road bridge in the interval 1960 to 1980. This finding, based on few surveys under unknown stream flow conditions, is not consistent with previous research, with the findings of increased sediment loads in the Tully catchment (Chapter 4.3) and with results from the South Johnstone catchment, 50 km to the north. Connor (1986) analysed digitised vertical air photos from 1942 to 1983 and estimated an annual sediment accumulation in the South Johnstone River of 100 000t. He suggested that this rate was increasing as more cane land, a greater proportion of which was erosion prone, was cultivated, that aggradation in relation to the original stream size was greatest in upstream reaches, and that economic losses occurred in both urban and rural areas as a result of this aggradation. Local Government and River Improvement Trust engineers have expressed concern that aggradation in coastal streams of Queensland's wet tropics is both increasing flooding and negating drainage improvements undertaken in flood plain areas (Capelin and Prove, 1983).

Because no comprehensive analysis of channel aggradation in the Tully catchment is available, this aspect of sediment yield response to land use intensification warrants further investigation.

4.4.2 Data and Methods:

In the period since the QWRC stream gauging station 113006 was established at Euramo in 1972, 115 cross-section surveys have been undertaken, up to and including July 27th, 1993. Hydrographers surveying stream characteristics often make small changes to the location of the site surveyed according to individual preference and river stage. QWRC hydrographers responsible for surveying the Tully River report that the characteristics of the Euramo site are such that no changes have been made to the site surveyed over time, or in relation to discharge. Discharge, gauge height, cross-sectional area, channel width, and date and time of survey data were obtained from hydrographer's field note books held at the Mareeba, north Queensland office of the QWRC. These data are used to investigate channel aggradation in the Tully River over this 21 year period. Ten of the 105 observations were discarded due to minor problems of inconsistency and illegibility.

Providing that the hydrographic surveys are consistently executed, the average stream bed elevation for a given observation can be calculated using the simple formula:

$BE = Gh - (A/W)$, where [Eqn. 4.4.1]

BE = bed elevation,

Gh = gauge height,

A = water cross-sectional area, and

W = stream width.

The strong correlation between discharge and cross-sectional area for Euramo surveys (Fig. 4.4.1) indicates that the surveys are of sufficient precision for the analysis.

Equation 4.4.1 assumes a rectangular channel cross-section. The actual channel shape is irregular trapezoidal, requiring either a stepwise analysis or correction for changing geometry with increasing discharge. In this analysis the latter is applied. This simple method of determining the bed elevation, and thus the aggradation history of the stream for the survey period, must also be interpreted in the context of changes in stream width. In this investigation, channel geometry and stream width were accounted for using regression analysis and analysis of residuals.

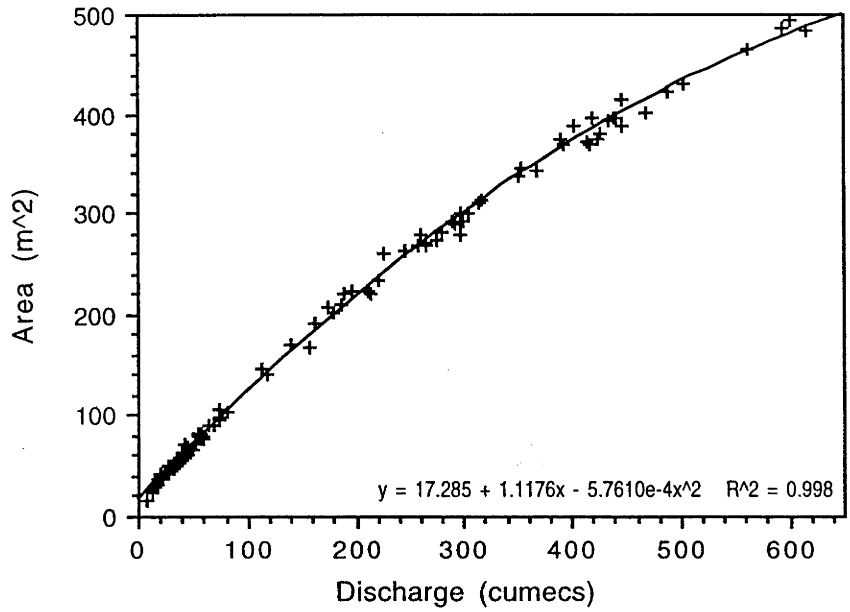


Fig. 4.4.1
Relationship between discharge and cross-sectional area for the Tully River at Euramo.

4.4.3 Results and Interpretation

The relationship between bed elevation and discharge (Fig. 4.4.2) has the form:

$$BE = 1.495 + 1.2466 \times 10^{-3} Q \quad \text{[Eqn. 4.4.2]}$$

$(r^2 = 0.786; n = 105)$

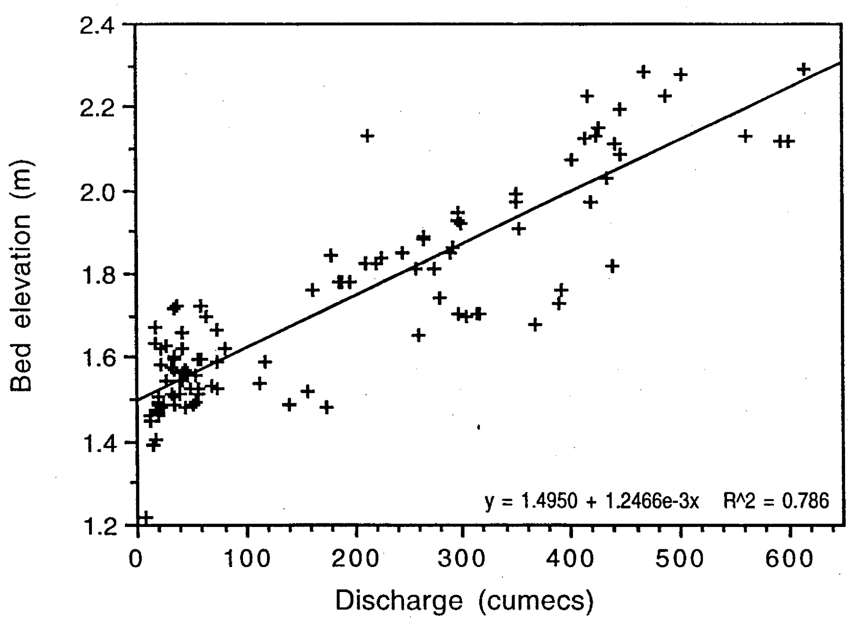


Fig. 4.4.2
The relationship between discharge and bed elevation in the Tully River at Euramo.

The residuals from this relationship, regressed against the time of observation, give an estimate of the change in bed elevation due to changed channel geometry, with the effect of discharge removed. This result is illustrated in Fig. 4.4.3, and shows that a lowering of the mean bed elevation by about 0.19 m over the 21 years of record is likely, as indicated in Eqn. 4.4.3:

$$BE = 6.915 \times 10^{-2} - 2.4908 \times 10^{-5}\, T \qquad \text{[Eqn. 4.4.3]}$$

$(r^2 = 0.309;\ n = 105)$

where T = time in days since observations began.

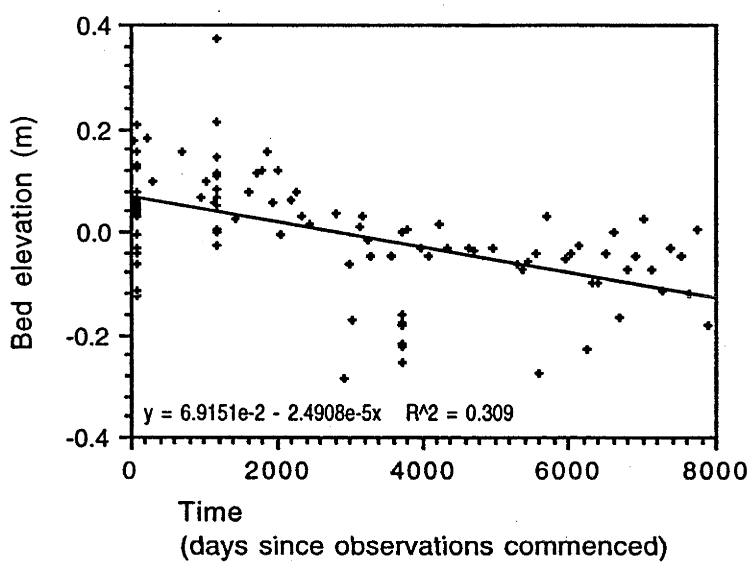


Fig. 4.4.3
The relationship between time and bed elevation, corrected for discharge, in the Tully River at Euramo.

The results obtained in equation 4.4.3 include a contribution from changes in channel width, which is also related to discharge (Fig. 4.4.4). Analysis of the change over time in the residuals from this relationship (carried out as for bed elevation, above) suggests channel narrowing over the 21 years of observations of about 1.5 m. The calculation:

$(\bar{x}\text{ area }(\bar{x}\text{ width} + 1.5/2)^{-1}) - (\bar{x}\text{ area }(\bar{x}\text{ width} - 1.5/2)^{-1})$

results in an estimate of about 0.03 m (16 %) of bed degradation being attributable to channel narrowing.

These results indicate the following contributions to changes in mean bed elevation in the Tully River over the last two decades:

Change due to stream bed degradation	- 0.16 m
Change due to channel narrowing	- 0.03 m
Total change	- 0.19 m

Separation of the data set into four approximately equal time periods shows that most of the change in bed elevation occurred between the period 1972 - 1976 and the following period (1977 - 1982) and bed elevation appears to have been relatively stable since that time (Fig. 4.4.5 (a) and (b)). There is a significant difference between the mean bed elevation (corrected for discharge) during the 1972-76 period and that for each of the subsequent periods (t-test; $p \leq 0.01$). There are no significant differences between the mean bed elevations for the periods 1977-82, 1983-87 and 1988-93. The difference between the means for the 1972-76 period and 1988-93 period (Fig. 4.4.5 (b)) suggest a stream degradation of 0.14m, consistent with the 0.19 m previously calculated.

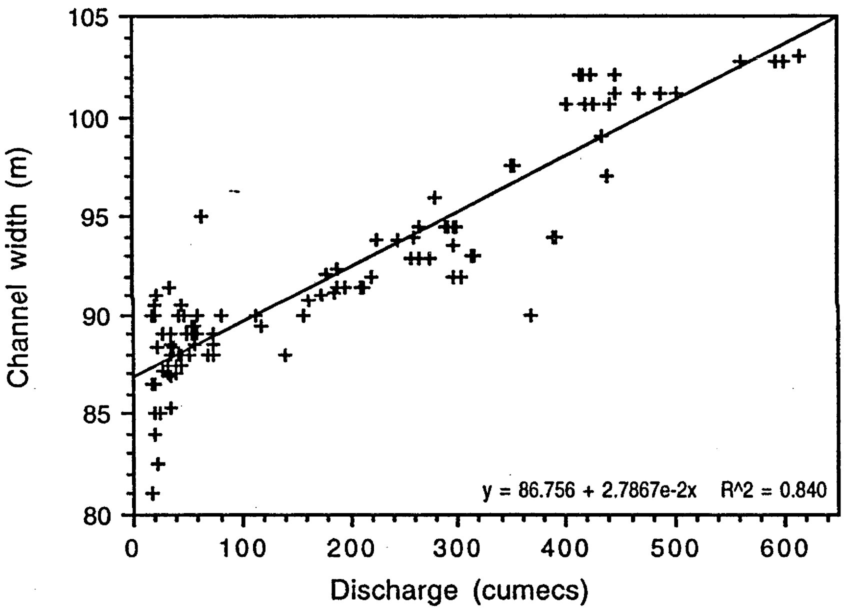
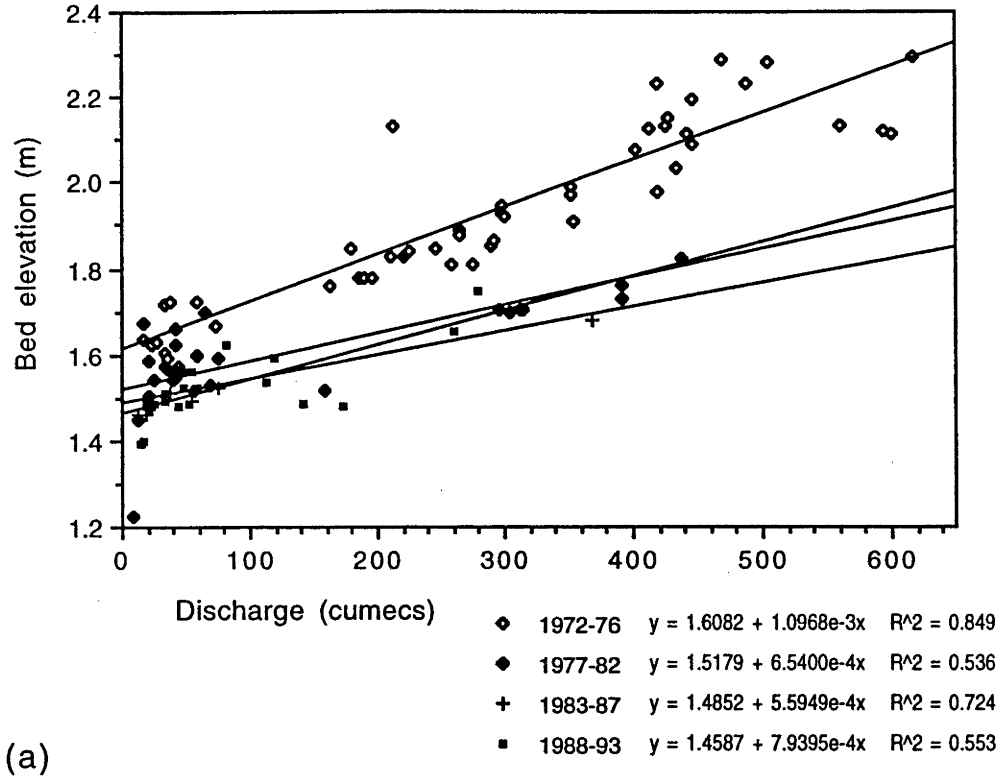


Fig. 4.4.4
The relationship between discharge and channel width; Tully River at Euramo.



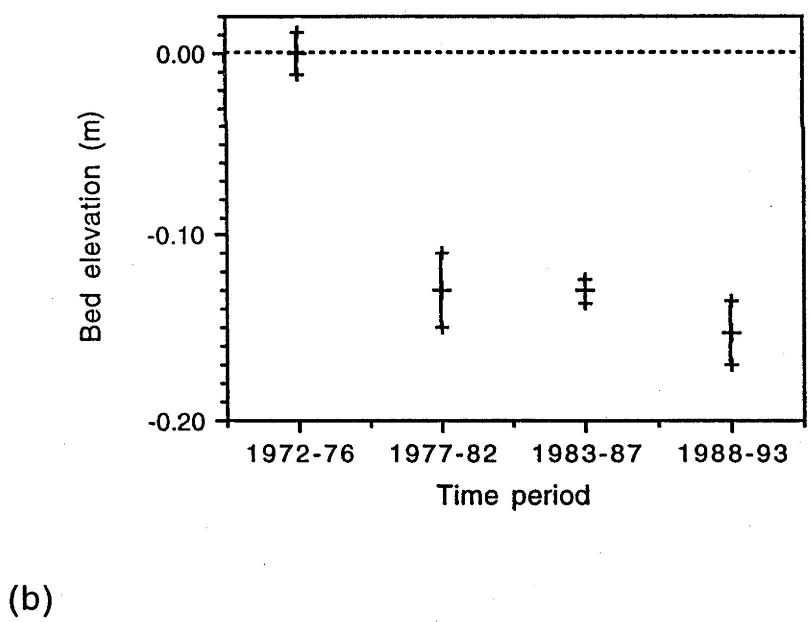


Fig. 4.4.5
The relationship between discharge and bed elevation (a) and the mean bed elevation ± S.E. in relation to the 1972-1976 mean (b), both corrected for discharge, for each of four time periods.

Assuming a mean channel width of 90 m and a bulk density of 1.6, the channel changes which have occurred are equivalent to a sediment yield of 0.8 $t.km^{-2}.yr^{-1}$ for each kilometre of stream channel affected. Twenty kilometres of bed degradation is equivalent to 30 % of the estimated mean annual sediment yield. However, little of this dominantly very coarse sand and fine gravel sediment would have reached the island fringing reefs of Rockingham Bay.

Channel narrowing of between 1 and 2 % of channel width appears to have occurred, possibly due to the interaction of increased suspended sediment concentrations due to land use change, and colonisation of stream banks, from which rainforest has been cleared, by a dense cover of tall, introduced grasses. Sediment trapping by these grasses leads to stream bank aggradation which narrows the channel. In addition, the dense mat of grass stems is itself likely to affect the hydrographers measurements. It is also unclear whether bed lowering is a partial cause of channel narrowing or *vice versa*.

Degradation of the Tully River stream bed is surprising given the land use history of the catchment and Connor's (1986) observations of continued aggradation in the South Johnstone River. Possibly the best explanation of the Tully River degradation pattern is that the bed had aggraded slightly in response to the large scale land clearing of the early 1960s, reaching a maximum during or prior to the 1972-1976 period. Following this, the bed degraded by about 0.15 - 0.20 m and has remained fairly stable over the last 15 years. Another factor likely to have contributed to Tully River degradation is increasingly channellised stream morphology due to levee construction. Levees along the Tully River and its tributaries are constructed by both banana and sugar cane growers, in some cases under permit but often without authorisation. Finally, sand and gravel extraction from the Tully River may also be a factor. Accurate data on the volume of material extracted are not available, largely because much of the mining is carried out without permits by private operators.

In summary, there is no evidence of aggradation in the Tully River over the last two decades. The dominant trend is one of degradation, most of which occurred between the 1972-1976 and 1977-1983 periods. Since that time, the bed elevation has been relatively stable. Channel narrowing has also occurred during the period of record. Several factors, including episodes of land clearing, levee construction, sand and gravel extraction, increased suspended sediment concentrations, rainforest removal from stream banks, and colonisation of stream banks by introduced grasses, may have contributed to the subtle changes in channel morphology which have occurred. The available data indicate that the lower Tully River is essentially a conduit for sediments although it has been a significant source of coarse sediments, particularly during the early 1970s. Little of the eroded bed material could reach the island fringing reef sites in Rockingham Bay. The changes which have occurred are unlikely to have had a significant impact on hydraulic efficiency or the transport of sediments into the inshore zone.

4.5 SUMMARY:

The results of the Tully River catchment analyses suggest that the sediment yield response of this catchment to land use change is consistent with results from a variety of widely differing environments, but at the lower end of the documented range of response magnitude. The conclusion that this catchment responds at the lower end of this range is attributed to the tectonic stability, low inter-annual rainfall variability, soils of relatively low erodibility and high permeability, the absence of land clearing on steeplands, and the adoption of zero tillage/residue retention cropping practices on much of the Tully cane lands, as pointed out in Chapter 3. An additional factor is that, in both the 1988 and 1990 wet seasons the major runoff events monitored occurred in mid-February and mid-March respectively, by which time most of the cane crop had achieved good canopy cover.

In the context of sedimentation impacts on offshore coral reefs and of the ability of those reefs to incorporate a sediment yield signal, the situation is considerably more complex. Two main factors are involved. Firstly, in the coral reef context, the effective increase is likely to be greater than the interpreted overall increase. This is because the increase in sediment yield appears to be non-linear across the range of discharges monitored. The largest increases generally occur at the highest stream flows, and it is only at the highest stream flows that fluvial sediments are transported directly to the fringing reef sites. Secondly, changes in land use, including deliberate drainage of much of the flood plain and some "river improvement" works, have probably resulted in some increase in the hydraulic efficiency of the catchment. As a result, sediment plume movement to fringing reef sites is likely to be more frequent, although of shorter duration, for a given precipitation rate and volume. Changes in the channel geometry of the lower reaches of the Tully River are so small as to have had negligible effect on hydraulic efficiency.

The most significant finding from this investigation, however, is the difference between the trend in the reconstructed sediment yield, corrected for temporal variation in estimated rainfall erosivity (Fig. 4.3.2), and the trend in estimated sediment yield due to changing catchment susceptibility to water erosion (Fig. 4.3.1). An indication of the magnitude of this difference is given by the simple expedient of calculating the difference between the 1926 and 1990 sediment yield based on the linear trend between those years. Using the sediment yield estimated from land use and management only, the overall trend for this period is an increase in sediment yield by 240 %. After adjusting for rainfall erosivity a decrease of 40 % is estimated. The estimated decadal mean sediment yield for the period 1946 -1955 is about 17 % greater than that for the 1970 - 1979 period, and 75 % greater than for 1981 - 1990, although relatively little land use intensification occurred prior to and during the 1946 - 1955 period (Fig. 2.3.2).

While it is acknowledged that both the sediment yield and rainfall erosivity calculations are estimates only, the difference between the potential and actual sediment yields has important implications for environmental managers in both terrestrial and marine ecosystems, and for the reconstruction of sediment yields using coral cores as environmental recorders.

CHAPTER FIVE

FLUVIAL INPUTS TO ROCKINGHAM BAY DURING THE 1988 AND 1990 WET SEASONS

CONTENTS

5.1	INTRODUCTION
5.2	METHODS
5.3	RESULTS
5.4	DISCUSSION
5.5	SUMMARY

5.1 INTRODUCTION

Runoff from catchments draining to the Great Barrier Reef Lagoon is a cause of concern to marine parks managers, scientists, politicians and the general public in Queensland and is a topic which continues to attract debate in both political circles and the scientific literature (eg. Walker 1991, Bell and Gabric 1991, Kinsey 1991a). Runoff generated in agricultural or pastoral lands, logged catchments and urban areas has the potential to cause damaging impacts on coastal ecosystems, including mangroves and coral reefs, due to sedimentation and turbidity effects, or of ions transported in solution or adsorbed onto the sediments. Reduced salinity can result in coral death with subsequent overgrowth by algae, bleaching due to zooxanthellae expulsion, and also territorial fish death and vagile fish displacement as occurred on fringing reefs of the Keppel Group of islands after the Fitzroy River flood of January, 1991 (van Woesik, 1991).

The purpose of this chapter is twofold. Firstly, existing knowledge of sediment and nutrient dynamics in nearshore GBR Lagoon waters relevant to this study is briefly reviewed. Secondly, the distribution of sediments and certain solutes in Rockingham Bay during the 'wet seasons' of 1988 and 1990, with particular reference to the coral coring sites discussed in Chapter 6, is investigated.

5.1.1 Oceanographic context and sediment plume dynamics:

The physical oceanography of the Great Barrier Reef region has been reviewed by Andrews and Pickard (1990) who state that frictionally-dominated nearshore currents respond closely to wind forcing (Wolanski and Ruddick, 1981) and, given that winds in the central GBR are southerly for most of the year (Wolanski, 1982a), the seasonal drift direction in the nearshore zone is northward for most of the year (Andrews, Mitchell and Bellamy, 1983). This is in contrast with the pattern in the outer Lagoon (Andrews, 1983; Andrews *et al.*, 1983) and the northern Lagoon (Wolanski and Thompson, 1984; Wolanski and Pickard, 1985) where a southerly drift, with seasonal variation, is common.

Wolanski and van Senden (1983) investigated the pattern of movement of the Burdekin River plume during the 1981 wet season and found that it moved northward along the coast, only reaching the outer reefs about 200 km north of the river mouth. They suggested that the volume of water input from the river, in combination with rainfall onto the Lagoon, was sufficient to generate a northward geostrophic longshore current of some 5 - 10 $cm.sec^{-1}$. A dynamically similar pattern is reported for the Nicaraguan east coast (Roberts and Murray, 1983). As the Burdekin plume moves northward from the river mouth, it widens away from the coast (Wolanski and van Senden, 1983; Wolanski and King, 1988).

Wolanski and van Senden (1983) map low salinity waters extending to the northeast from the Hull, Tully and Murray Rivers from 20.1.1981 to 3.4.1981. However, they have no data from within Rockingham Bay.

Other observations of sediment plume movement in the GBR Lagoon have been made, but without accompanying quantitative data. For example, after cyclone Winifred (which crossed the coast at Cowley Beach on 1.2.1986) extensive river plumes were observed during an aerial survey on 5.2.1986. That from the Herbert River extended as far as the northern end of the Palm Group (c. 18 km) and the plume from the Russell/Mulgrave Rivers extended north (c. 10 km) to the Frankland Islands (Dutton, 1986). Johnson et al. (1986) report muddy river plumes extending as much as 30 km offshore during that event.

Rockingham Bay differs physiographically from other sites where sediment plumes have been observed and there is no quantitative data on sediment plume dynamics in Rockingham Bay.

Rockingham Bay is more enclosed than other sites with Hinchinbrook Island in the south and Tam O'Shanter Point and Dunk Island in the north restricting circulation and influencing wave patterns. There is a strong northeast-southwest component in the ebb-flood circulation in Rockingham Bay, tidal velocities ranging from c. 0.25 $m.s^{-1}$ in the outer bay to 1.5 $m.s^{-1}$ at the northern end of Hinchinbrook Channel (Hydrographic chart Aus 833).

The limited information on sediment plume movement in Rockingham Bay is as follows:

(i) On aerial photography flown on 7.6.1961 a sediment plume is evident east-northeast of the Tully mouth. The plume is c. 29 km^2 in area and extends to 1.7 km west of Bedarra Island (Fig. 5.1.1). There is also a small plume extending c. 1.8 km radially from the Murray mouth, the tone of which implies more turbid water than that from the Tully. No Hull River plume is evident. Rainfall in May, 1961 was about 30 % of the mean for that month, and in June was only about 30 % greater than the mean.

(ii) Following the February, 1986 flood (cyclone Winifred) the Tully River plume passed largely to the south of Coomb Island (D. Hopley, 1987, pers. comm.).

(iii) Pringle (1986) suggests that longshore drift of sediments from the Hull, Tully, and Murray Rivers is southward. Pringle's analysis is based on air photo interpretation of the morphology of river mouth deposits. She suggests that the presence of Tam O'Shanter Point and the protection from the dominant southeast waves induces southward longshore drift of beach sands from the Murray River, the effect decreasing northward for the Tully and Hull Rivers.

(iv) By analogy with other sites and given the large discharge volume from the Tully River, a northward geostrophic current would be expected to develop in Rockingham Bay, modified by local wind and tide patterns (as discussed in Chapter 2.2.1).

5.1.2 Sedimentological context:

Seismic refraction results (Searle *et al.*, 1980; Harvey and Searle, 1983) indicate rates of postglacial sedimentation in shelf waters. Terrigenous sedimentation rates are indicated in cores from inter-reefal sediments (Johnson and Searle, 1984) and from reefs (Johnson, Cuff and Rhodes, 1984), and the distribution of carbonate content of surficial sediments approximates the distribution pattern of modern sedimentation (Orme and Flood, 1980). Terrigenous sediment distributions are also indicated by the difference between stable carbon isotope ratios ($^{13}C/^{12}C$) of terrestrial and marine organic matter (Gagan, Sandstrom and Chivas, 1987).

The general pattern of sedimentation in the GBR Lagoon which emerges from these and other studies indicates that postglacial sedimentation is generally less than c. 25 m thick. Terrigenous sedimentation is largely confined to the inner shelf region, although in the deeper sections of cores from outer shelf reefs terrigenous sediments are present (Johnson, Cuff and Rhodes, 1984), associated with lower sea levels and coastlines east of their present position.

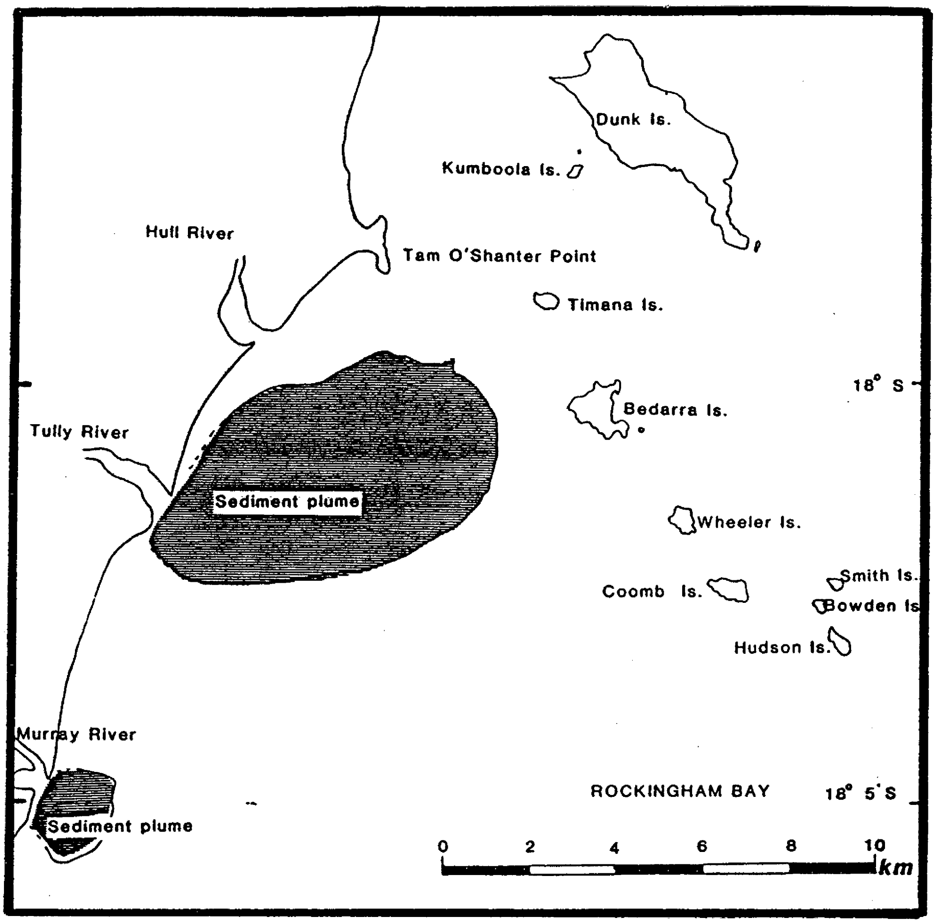


Fig. 5.1.1
Sediment plume distribution in Rockingham Bay, 7.6.1961; mapped from vertical air photography (1:86 000).

Chivas, Torgerson and Andrew (1983) used ^{210}Pb dating to determine sedimentation rates, and stable carbon isotope ratios to determine the ratio of terrestrial to marine organics in bottom sediments in the vicinity of Hinchinbrook Island. Their data set included four sites from central Rockingham Bay, between 6 and 17 km to the southeast of the Tully River mouth. Their results indicated sedimentation rates of 5.0 ± 0.5, 2.2 ± 0.5, 7.0 ± 1.0 and 3.8 ± 0.5 $mm.yr^{-1}$ at these sites with a mean terrestrial contribution of about 45 % at the three sites nearest the shore and of 10 % at the offshore site (about halfway between Goold and Coomb Islands). Belperio (1983), using different mathods, estimated sedimentation rates of < 0.1 $mm.yr^{-1}$ in 19 of 30 cores analysed from Halifax, Cleveland and Bowling Green Bays, with a maximum of 0.4 $mm.yr^{-1}$.

5.1.3 Nutrient dynamics:

The nutrients of greatest ecological significance in the GBR region are N and P. Nitrogen is the major limiting nutrient for phytoplankton production (Furnas, 1988) in inter-reefal waters, although certain species (eg. *Oscillatoria (Trichodesmium)* are nitrogen-fixing and may bloom independently of ambient nutrient (particularly N) concentrations (Revelante and Gilmartin, 1982). Increased phosphorus concentrations have a damaging effect on calcification (Simkiss, 1964) and the biogeochemistry of corals (Rasmussen, 1988; Rasmussen and Cuff, 1990). Increased phosphorus also increases coral mortality, preferentially facilitates algal growth and alters coral reef community structure (Walker and Ormond, 1982). In circumstances where N-limited phytoplankton blooms occur, a nutrient imbalance leaving "surplus" nutrients (eg. phosphorus) is possible.

Rockingham Bay lies largely within the nearshore ($\leq$ 10 m depth) zone defined by Furnas (1991b), who demonstrated that no latitudinal gradient of dissolved organic nitrogen (DON) occurred in that zone in northern and central GBR waters (although no data from Rockingham Bay was presented). However, latitudinal variation occurred in some inorganic N species and in particulate organic N (PON). No cross-shelf gradient in DON was observed either, although PON was consistently higher in the nearshore zone as a result of fluvial inputs.

Nutrient concentrations in the GBR Lagoon vary on cross-shelf and latitudinal gradients (Furnas, 1991b), and on event-based (Walker and O'Donnell, 1981), seasonal (Furnas, *et al.*, 1990) and possibly secular time-scales (Bell and Gabric, 1990). Event-scale nutrient enhancement in nearshore areas may occur as a result of river runoff and bottom sediment resuspension resulting from cyclonic activity. For example, one week after cyclone Winifred (February, 1986), DON and PON were greater by 24 % and 42 % respectively than normal summer concentrations in central GBR waters (Furnas, 1991b).

Some information on nutrient behaviour, particularly in relation to sediment dynamics, is available from other nearshore, semi-protected embayments in the central GBR Lagoon. N and P concentrations were better correlated with Secchi disc readings than with salinity in Cleveland Bay (160 km south of Rockingham Bay; water depth of 10 m), an indication that bottom sediment resuspension was an important determinant of nutrient levels in the water column (Walker and O'Donnell, 1981). Ullman and Sandstrom (1987) determined nutrient fluxes from sediments to the water column at stations in < 5 m depth in Bowling Green Bay, about 50 km south of Walker and O'Donnell's site. They found that inner shelf sediments were a source of both N and Si, but a sink for P, with resuspension of bottom sediments by wave action likely to result in increased N concentrations in the water column but neglible increases for P and Si. Enhanced primary production in relation to sediment resuspension was indicated by a strong relationship between turbidity and chlorophyll (Walker and O'Donnell, 1981).

5.1.4 Sediment plume monitoring:

Monitoring of fluvial sediment plumes offshore from catchments in the wet tropics poses a number of problems, differing according to the method proposed. In the case of satellite remote sensing, for example, there is often no plume to observe by the time the clouds which brought the runoff-producing rain have dispersed, due to the rapidity with which sediment plumes in the Great Barrier Reef Lagoon are dispersed (Wolanski and Jupp, 1984). Although this problem is of less importance in catchments where the area of high rainfall is remote from the river mouth, such as the Fly River, PNG (Wolanski, Pickard and Jupp, 1984), for the wet tropical Queensland coast where mountain ranges are close to the coast, the presence and dispersal of cloud cover and of sediment plumes may be concurrent. This limitation may be partly rectified by interpolation using data from pixels in cloud free patches in the image (Neil, 1987). However, a fundamental requirement of satellite-based data gathering is ground-truthing of the image.

The combination of sediment plume, sufficiently low cloud cover to allow a reasonable probability of some ground control points being in cloud free areas, sea-state low enough to permit sampling and a satellite overpass date is quite uncommon in the wet tropics during the wet season, and did not occur during fieldwork in 1987-88 or 1990. An additional limitation is the frequency of overpasses. In the region in question, a sediment plume could form, propagate and disperse, entirely within the period between overpasses.

Sediment plume monitoring by photo interpretation has been used to track glacial meltwater plume movement in a small fjord (Dowdeswell and Cromack, 1991). The small areal extent of the plume and the presence of an elevated site allowed the use of photogrammetrically-corrected terrestrial photography at one hour intervals, linked to boat based sampling to derive a semi-quantitative picture of plume dynamics. This approach is limited to relatively small plumes where elevated sites are available and in clear weather. For larger scale plumes air photography (vertical or oblique) provides an alternative, also limited by cloud cover.

As a result of these limitations, boat based surveys of Rockingham Bay were the option considered most feasible for this study, accompanied, when cloud conditions permitted, by aerial surveys using oblique photography. A submersible Analite turbidity meter and a data logger were moored at Bedarra Island during the 1987 - 1988 sampling period.

5.2 *METHODS.*

5.2.1 Field methods:

Dip samples, from a depth of 10 cm, were obtained from an open boat along transects from the mouth of the Hull River to Bedarra Island (RoA), and from the Tully River to Coomb Island (RoB) during the period 9.1.1988 to 14.3.1988 (Fig. 5.2.1). River mouth samples were obtained offshore from the bar at both rivers. The transects from the Hull River to Bedarra Island and from the Tully River to Coomb Island were sampled on six occasions during this period (concentrated in the period when runoff was occurring in the Tully River), and samples were obtained at Bedarra Island 18 times. No equipment for vertical profiling of salinity or turbidity was available for this study. As a result, surface water samples only were obtained.

An Analite nephelometer linked to a data logger and housed in a watertight casing was deployed on the fringing reef at Bedarra Island in order to continuously monitor turbidity at this site. Substantial increases in

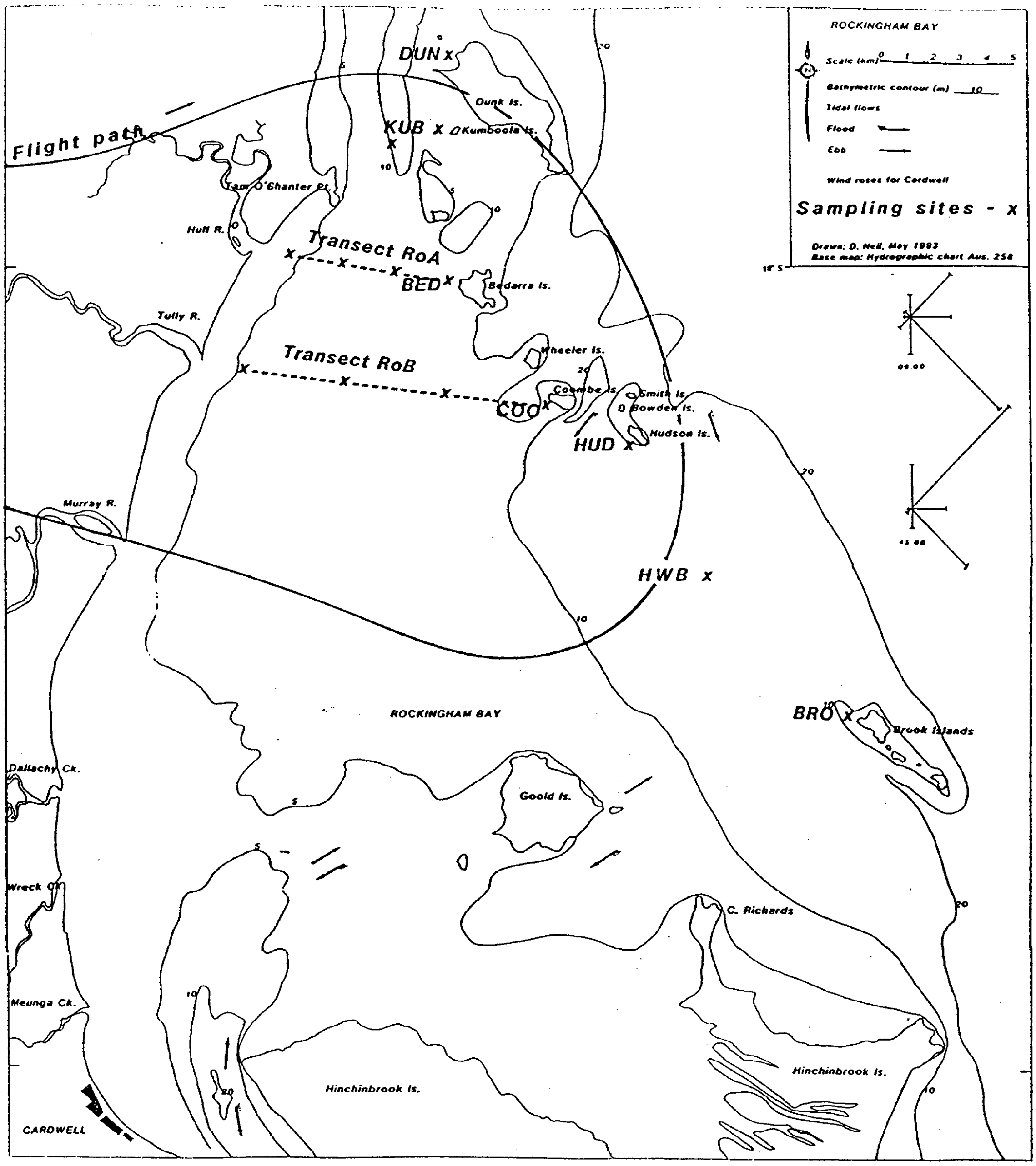


Fig. 5.2.1
Location of water sampling sites in Rockingham Bay and the flight path for aerial observations of sediment plume movement, 25.3.1990 and 3.4.1990.

turbidity, attributable entirely to algal growth on the probe, were measured over 2 day periods (+ 21, 38, 479 %), 3 day periods (+ 7, 19 and 28 %), a 4 day period (+ 1077 %) and a 5 day period (+ 375 %). Without a self-cleaning mechanism, such a turbidity probe is of limited use in warm, shallow tropical waters, and the results of this work are not further discussed.

During the 1990 wet season (March - April) dip samples were obtained in the same manner as during 1987-88 and returned to the laboratory for turbidity analyses. Selected sub-samples were refrigerated and stored for further analysis. During this period the transects from the mouth of the Hull River to Bedarra Island and from the Tully River to Coomb Island were sampled. Additional samples were obtained from Brook and Hudson Islands in the south, at Kumboola and Dunk Islands in the north, and at a number of other sites in Rockingham Bay.

During these periods, sampling sites were chosen with the following objectives:

(i) to monitor the movement of the Tully River plume, and its composition, in Rockingham Bay.

(ii) to monitor suspended sediment concentrations at sites from which coral cores would be / had been obtained.

(iii) to collect calibration samples while servicing the turbidity meter deployed at Bedarra Island.

There is some bias in the sampling because sea conditions can limit the times when it is safe to go to sea in an open boat. It is often the case (eg. during a tropical cyclone) that the greatest sediment mobilisation and transport, in both marine and terrestrial environments, is accompanied by gale-force winds making boat-based sampling impossible.

Aerial surveys, during which oblique photographs were taken, were undertaken on March 25th, 1990 and April 3rd, 1990 along the flight path shown in Fig. 5.2.1.

An important consideration in this study is the extent to which the coral core record at sites in Rockingham Bay could be corrupted by inputs from streams other than the Tully/Murray, with the Herbert River the most likely such source. Attention was paid to this possibility during both boat-based and aerial surveys.

5.2.2 *Analytical methods:*

Turbidity was measured using an Analite Model 155 digital nephelometer (BWD Precision Instruments, Australia) with a measuring range of 0.1 to 2000 NTU. The instrument was zeroed using deionised water (Queensland

Ethicals, Australia) prior to each set of measurements, rinsed in deionised water between determinations and checked for drift at the completion of analyses. Drift was generally $\leq$ 0.2 NTU over the measuring period, and was linear. Corrections for drift were made to the results.

The turbidity and suspended sediment concentration (SSC) calibration was derived by passing water samples (500ml) through predried, preweighed 0.45 µm pore size filters at low vacuum. The filter papers were oven dried (100°C) and reweighed (to 0.0001g) to determine SSC. There is a significant linear correlation between turbidity and SSC (Fig. 5.2.2).

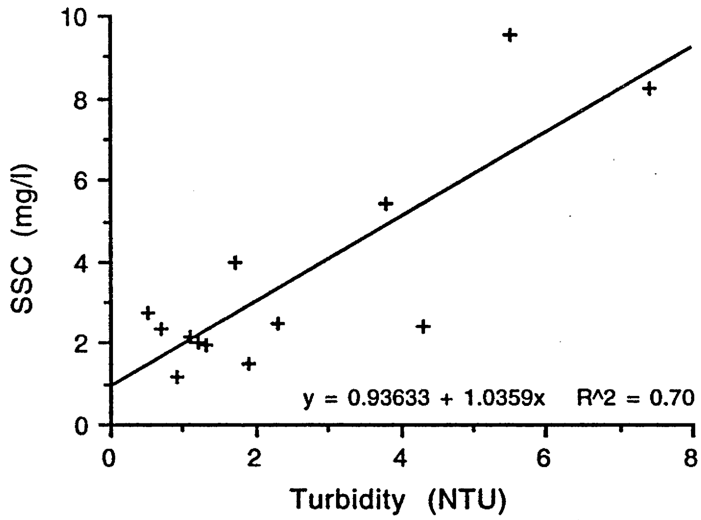


Fig. 5.2.2
Calibration curve for the relationship between turbidity (0-7.4 NTU) and suspended sediment concentration (samples from Rockingham Bay; n = 13).

The regression equation fitting Fig. 5.2.2 is:

SSC = 0.936 + 1.036.Turbidity (n = 13; r^2 = 0.70) [Eqn. 5.2.1]

Salinity determinations were made with a Unilab conductivity meter for the 1987-88 sampling period. Selected samples were frozen and the filtrates subsequently analysed for solute chemistry, using the methods described in Chapter 3.2.3, and the filter paper residues for sediment mineralogy using X-ray diffraction. Salinity determinations for the 1990 sampling period are derived from Na concentrations.

5.3 RESULTS.

5.3.1 Spatial variation of water quality in Rockingham Bay, January - March, 1988:

Fig. 5.3.1 shows the hydrograph and sedigraph for the Tully River during the 1987-88 sampling period, and suspended sediment concentrations at Bedarra Island (the nearest island site to the river mouth). The results suggest a background SSC at Bedarra Island of about 1.5 mg.L^{-1}. SSCs above the apparent background level occur in association with the fluvial events of 17.2 and 9.3.1988. However, there are a number of observations when SSCs are high, quite independent of river discharge and suspended sediment concentration, which can best be attributed to bottom sediment resuspension.

The highest SSC recorded at Bedarra Island during the summer of 1987-88 was 4.9 mg.L^{-1}, which occurred on January 27th while the river was at baseflow, and was still 3.0 mg.L^{-1} on the 29.1.1988. During this three day period, wind speeds in the range 8 - > 10 m.s^{-1} were maintained constantly (Aust. Bur. Met. 3 hr data). Similarly, SSC at Bedarra Is. on 1.3.1988 (after recession of the 17.2.1988 event) was 2.7 mg.L^{-1}, with no fluvial cause evident. However, in this case there was no associated strong wind observation either (Fig. 3.3.2). Bedarra Island SSCs in the period 9-13.3.1988 were much higher, in relation to Tully River discharge and SSC, than for the period 13-19.2.1988. Wind speeds at this time were in the range 5 - 8 m.s^{-1} (Fig. 3.3.2), although in the previous four days strong winds (to 18 m.s^{-1} at 06.00 and 15.00 hours on 6.3.1988) were experienced.

Sediment concentration gradients across Rockingham Bay during the 1987-88 sampling period are shown in Fig. 5.3.2. Peak discharge during the 1987 -

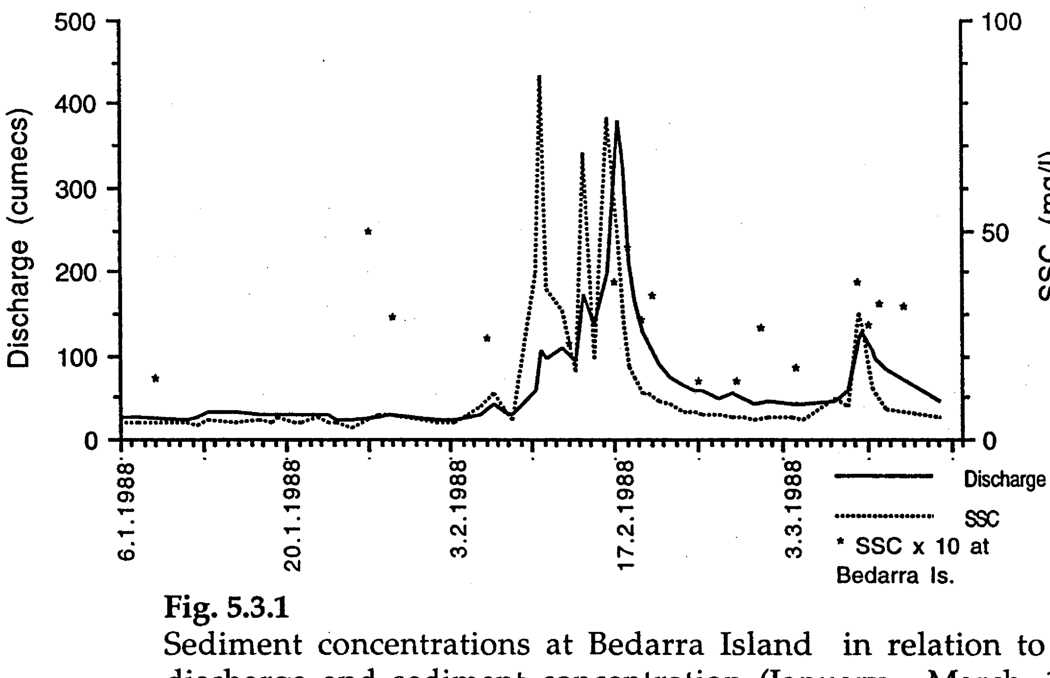


Fig. 5.3.1
Sediment concentrations at Bedarra Island in relation to river discharge and sediment concentration (January - March, 1988). Bedarra Island SSCs are exaggerated by a factor of 10.

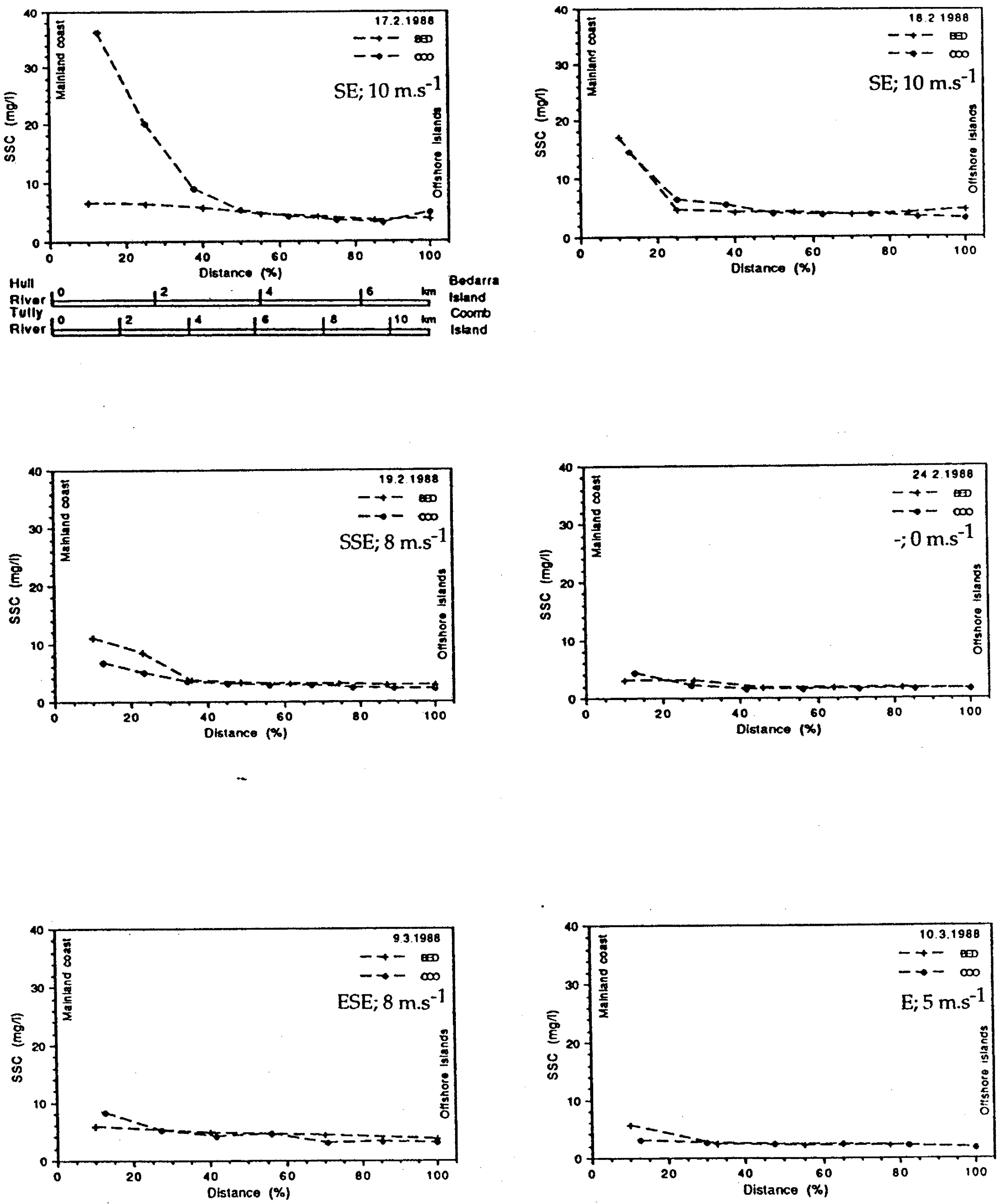


Fig. 5.3.2
Sediment concentration gradients across Rockingham Bay during the 1988 sampling period and wind speed ($m.s^{-1}$) and direction at the time of sampling; the legend refers to the coral coring sites at which the transects terminate; distances from the mainland are given in % to systematise the pattern - -> Bedarra = 7.3 km, -> Coombe = 11.2 km.

1988 wet season occurred on 17.2.1988 (380 cumecs). At this time, SSC in the Tully River at Euramo was 48 $mg.L^{-1}$, the maximum SSC recorded in Rockingham Bay was 36.4 $mg.L^{-1}$ adjacent to the Tully River mouth, and decreased seaward to 4.7 $mg.L^{-1}$ at Coomb Island (Fig. 5.3.2 (a)). From near the mouth of the Hull River, SSC decreased seaward to 3.7 $mg.L^{-1}$ at Bedarra Island. The tide was at late-flood at the time of sampling.

By the following day SSC at the river mouth had decreased to 14.5 $mg.L^{-1}$, and at bay and island sites (at the same stage of the tide) remained essentially unchanged. Observations on 19.2.1988 and 24.2.1988 indicated a continued steady decline in SSC at all sites (Fig. 5.3.2 (b-d)).

A minor streamflow peak of 128 cumecs occurred on 8.3.1988 with SSC of 30.2 $mg.L^{-1}$. Sampling on the Hull River to Bedarra Island and Tully River to Coomb Island transects was undertaken on the morning of 9.3.1988 (tide at mid-flood) and the afternoon of 10.3.1988 (tide at mid-ebb). At these observations SSC was between 5 and 9 $mg.L^{-1}$ at river mouth sites declining to $\bar{x}$ = 3.3 $mg.L^{-1}$ at island sites (9.3.1988; Fig. 5.3.2 (e)) and, on 10.3.1988, between 3 and 6 $mg.L^{-1}$ declining offshore to $\bar{x}$ = 1.8 $mg.L^{-1}$ (Fig. 5.3.2 (f)).

The general pattern evident from Fig. 5.3.2 is one of SSCs declining rapidly to 2 -3 km offshore and remaining relatively constant across most of the width of Rockingham Bay. SSC in Rockingham Bay, away from the coast, varied from about 1.4 to 6.8 $mg.L^{-1}$ during the sampling period. There is some evidence of an increase in SSC at the seaward end of the RoA transect and SSC at Bedarra Island is generally higher than at Coomb Island

A summary of the suspended sediment concentrations at Coomb and Bedarra Islands during the 1988 sampling period is given in Table 5.3.1. The minimum concentrations observed during this period define a "background" suspended sediment concentration, estimated at 1.4 $mg.L^{-1}$.

Site	n	mean	std.dev.	c.v.	min.	max.
		($mg.L^{-1}$)				
Bedarra Is.	18	3.6	2.2	61	1.4	6.8
Coomb Is	6	2.6	1.2	44	1.4	4.7

Table 5.3.1
Descriptive statistics of suspended sediment concentrations in Rockingham Bay waters adjacent to nearshore islands (coral core sites; 1988 data).

5.3.2 Spatial variation of water quality in Rockingham Bay, 1990 wet season:

5.3.2.1 Suspended sediment:

Observations based on boat-based and aerial surveys are presented in chronological order below. Peak discharge in the Tully River occurred at 04.30 hrs on 24.3.1990. By 12.00 hrs on 25.3.1990 river stage had dropped c. 0.60 m and by 18.00 hrs was c. 0.95 m lower than the peak. Between 15.00 and 15.30 hrs on 25.3.1990 a flight was undertaken by light aircraft (flight path shown in Fig. 5.2.1). At this time, Q was c. 830 cumecs and SSC about 33.4 $mg.L^{-1}$ (Fig. 5.3.3), 80 % and 25 % respectively of the maxima recorded during the flood. The tide was low and there was a light (3 $m.s^{-1}$) northerly wind. Contrasting these results with the wind data for the same period (Fig. 3.3.4) suggests that bottom sediment resuspension played no role in the SSC in Rockingham Bay waters in the March 27th - 29th period, but may have contributed significantly to the SSCs observed during the first week, and on the 12th, of April. The restriction of the Tully River sediment plume close inshore at this time (see below) supports this conclusion.

Sediment plume distribution at the time of the flight is shown in Fig. 5.3.4 and had the following characteristics:

(i) Sediment-laden water from the Murray River was confined to within about 1 km of the river mouth and extended northward toward the Tully River plume, with which it merged (Plate 5.1).

(ii) High turbidity waters from the Hull River were confined to the vicinity of the river mouth and, at their seaward margin merged with the Tully River plume. Restriction of the Murray and Hull River plumes to quite close inshore occured in spite of the observations being made at low tide.

(iii) The Tully River sediment plume extended northward from about 1.2 km south of the river mouth (Plate 5.1). The landward boundary lay close to the coast north to Tam O'Shanter Point where it moved seaward (Plate 5.2). Note the high turbidity water adjacent to Tam O'Shanter Point on this Plate. The plume lost definition to the north of Dunk Island. The southern (seaward) boundary extended from the river mouth to the east-northeast, intersecting the northern end of Bedarra Island at which point it was about 5 km wide (Plate 5.2 and 5.3).

(iv) The sediment plume broke up around the islands, with some evidence of the development of island wakes (cf. Wolanski, Imberger and Heron, 1984) to the east of Timana Island (Plate 5.4) and of Woln-Garin Island (Plate 5.5). The plume was very patchy and poorly defined to the east of the northern Family Group islands (Plates 5.4 and 5.5). The photographic evidence indicates that turbidity in the vicinity of Kumboola Island was surprisingly low (Plate 5.4).

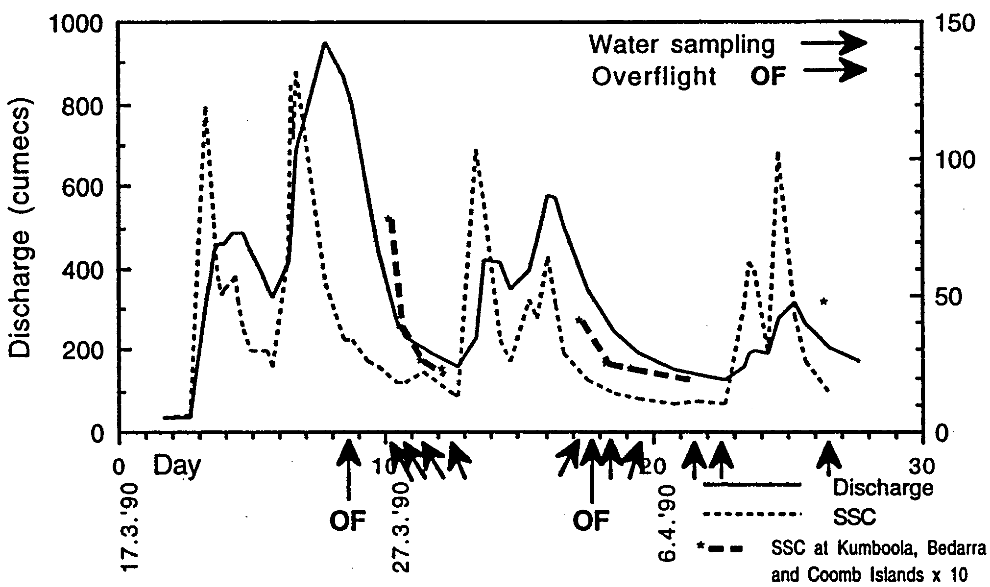


Fig. 5.3.3
Times of overflights and water sampling in Rockingham Bay in relation to river discharge and sediment concentration (March-April, 1990). Also shown are the mean sediment concentrations at Kumboola, Bedarra and Coomb Islands for each sampling. Note that these concentrations are exaggerated by a factor of 10.

(v) Adjacent to the southern islands of the Family Group (Coomb to Hudson) there was no sediment plume. However, there was 'reworked' sediment plume water in the form of relatively high turbidity water behind a tidal front (Plate 5.6), although this water body had much lower turbidity than in the sediment plume proper. Recirculation of river water by tidal oscillations probably plays an important role in keeping river waters in the vicinity of nearshore fringing reefs, even after the definable sediment plume has dissipated.

(vi) There was no evidence of a sediment plume moving northward from the vicinity of the Herbert River toward the southern islands of the Family Group.

(vii) Along the mainland coast of Rockingham Bay, south of the Murray River, there was high turbidity runoff water in a band a few hundred metres wide, probably from the many small coastal streams discharging to the bay in this area. There was no clear evidence of a sediment plume from the Herbert River flowing northward through the Hinchinbrook Channel.

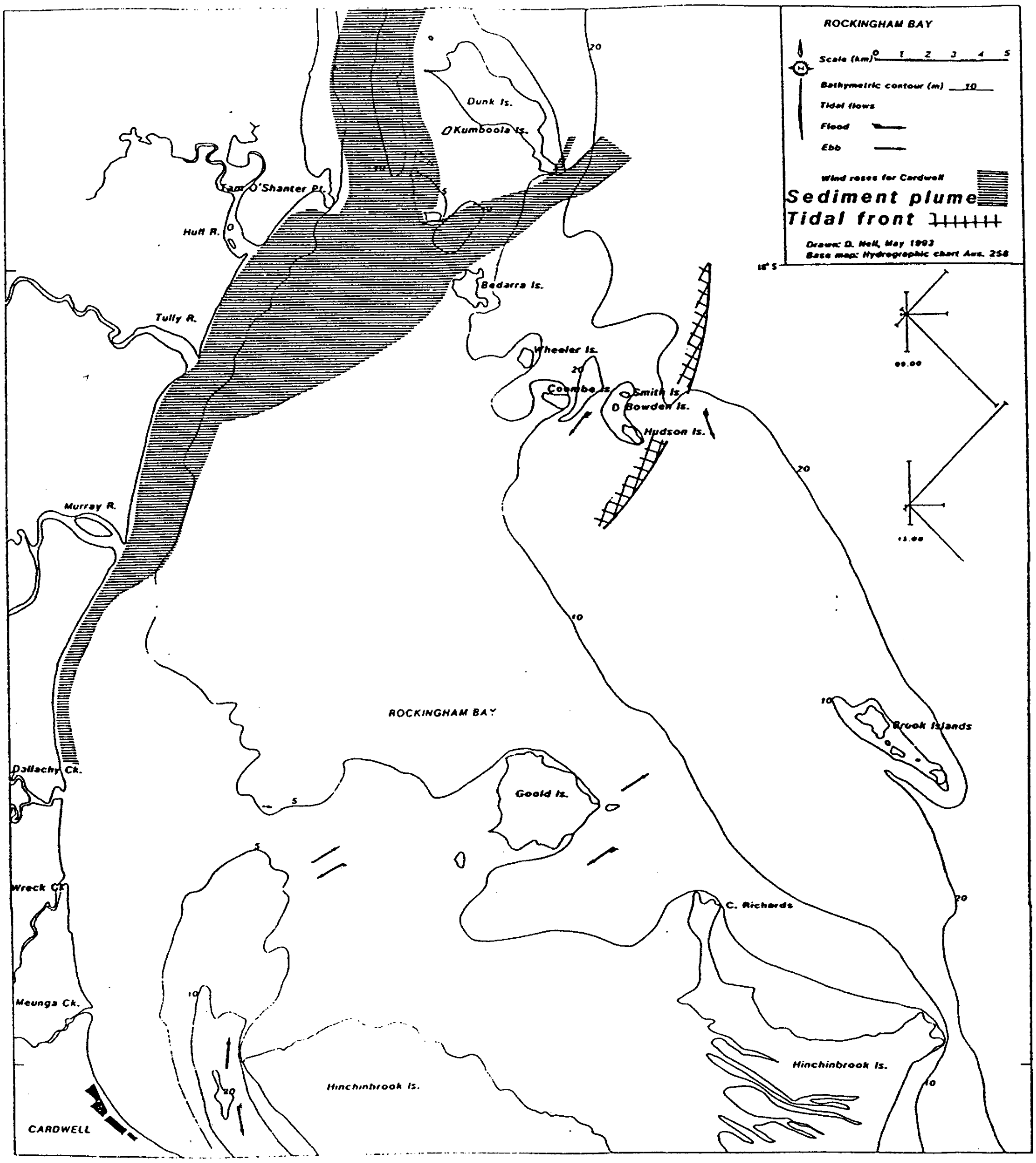


Fig. 5.3.4
Sediment plume distribution in Rockingham Bay, 27.3.1990; mapped from oblique air photography.

Plate 5.1
Sediment plume distribution in western Rockingham Bay, 25.3.1990; Murray River plume in foreground, Tully plume in background; Tully River top left, Dunk Island top right; -> N.

Plate 5.2
Sediment plume distribution in northern Rockingham Bay, 25.3.1990; Tam O'Shanter Point centre right, Bedarra Island upper left; note: contact of plume with Bedarra Island, separation from Tam O'Shanter Point; -> S.

Plate 5.3
Sediment plume distribution in Rockingham Bay, 25.3.1990; Bedarra Island lower right, Tully River in background; -> SW.

Plate 5.4
Sediment plume distribution in the vicinity of Family Group islands, 25.3.1990; Bedarra and Timana Islands centre right, Kumboola Island lower left; note: absence of plume near Kumboola, island wake at Timana; -> SE.

Plate 5.5
Sediment plume distribution to the east of Family Group islands, 25.3.1990; southern tip of Dunk Island centre foreground; note: absence of plume at left (east) of photograph, island wake at Woln-Garin Island; -> SE.

Plate 5.6
Tidal front of recirculated Tully River sediment plume waters to the south of Family Group islands, 25.3.1990; Smith, Bowden and Hudson Islands from left to right; -> ESE.

(viii) There was no evidence of high sediment concentrations in waters immediately adjacent to Family Group islands which could be attributed to sediment yield from those islands. However, because catchments on these islands are very small, it would probably be necessary to monitor runoff and local plume movement during or immediately after the rainfall event to ascertain the turbidity and extent of any sediment plumes generated on these islands. Although boat-based sampling was sometimes carried out during and following rainfall, sediment attributable to island sources was never observed.

Water sampling in Rockingham Bay during the 1990 sampling period was first carried out two days after the flight described above, on the morning of March 27th, 1990 at high tide, and three days after the flood peak. The maximum SSC recorded was 11.8 $mg.L^{-1}$ offshore from the Tully River mouth and decreased seaward to 7.0 $mg.L^{-1}$ at Coomb Island (Fig. 5.3.5 (a). From adjacent to the mouth of the Hull River, SSC increased seaward to a maximum of 6.2 $mg.L^{-1}$ at Bedarra Island. The highest sediment concentration recorded at bay or island sites (as distinct from the coastal sites near river mouths) was 10.0 $mg.L^{-1}$. The pattern indicated is one of sediment plume movement in a slightly more easterly direction than was the case on March 25th. The mean SSC at the Kumboola, Bedarra and Coomb island sites was 7.8 $mg.L^{-1}$ (Fig. 5.3.3).

By the afternoon of March 27th (early-flood tide; Fig. 5.3.5 (b)), SSC at the island sites had markedly decreased, although concentrations at the bay sites remained essentially unchanged. The mean SSC for the three island sites nearest the Tully River (Kumboola, Bedarra and Coomb) had decreased to 3.5 $mg.L^{-1}$ (Fig. 5.3.3), while at the Dunk Island site the SSC was much lower again (1.4 $mg.L^{-1}$), consistent with the aerial observation of plume dissipation to the northward of 25.3.1990.

On the March 28th (08.00 - 09.00) the SSC declined seaward from c. 4.0 $mg.L^{-1}$ at coastal sites to c. 2.4 $mg.L^{-1}$ at island sites. The mean SSC for the three near-river island sites was 2.42 $mg.L^{-1}$ and for Dunk in the north and Hudson in the south were 2.0 and 1.8 $mg.L^{-1}$, respectively. Within four days of the flood peak, SSC at island sites had returned to less than double the background levels.

Sediment concentrations were close to uniform throughout northern Rockingham Bay at 08.00 on March 29th. The mean SSC at Kumboola, Bedarra and Coomb Islands (2.3 $mg.L^{-1}$) remained slightly higher than at Dunk Island (1.9 $mg.L^{-1}$). As indicated in Fig. 5.3.3 discharge from the Tully River had declined to 170 cumecs by this time, still 6 times greater than baseflow but evidently insufficient to discharge significant quantities of

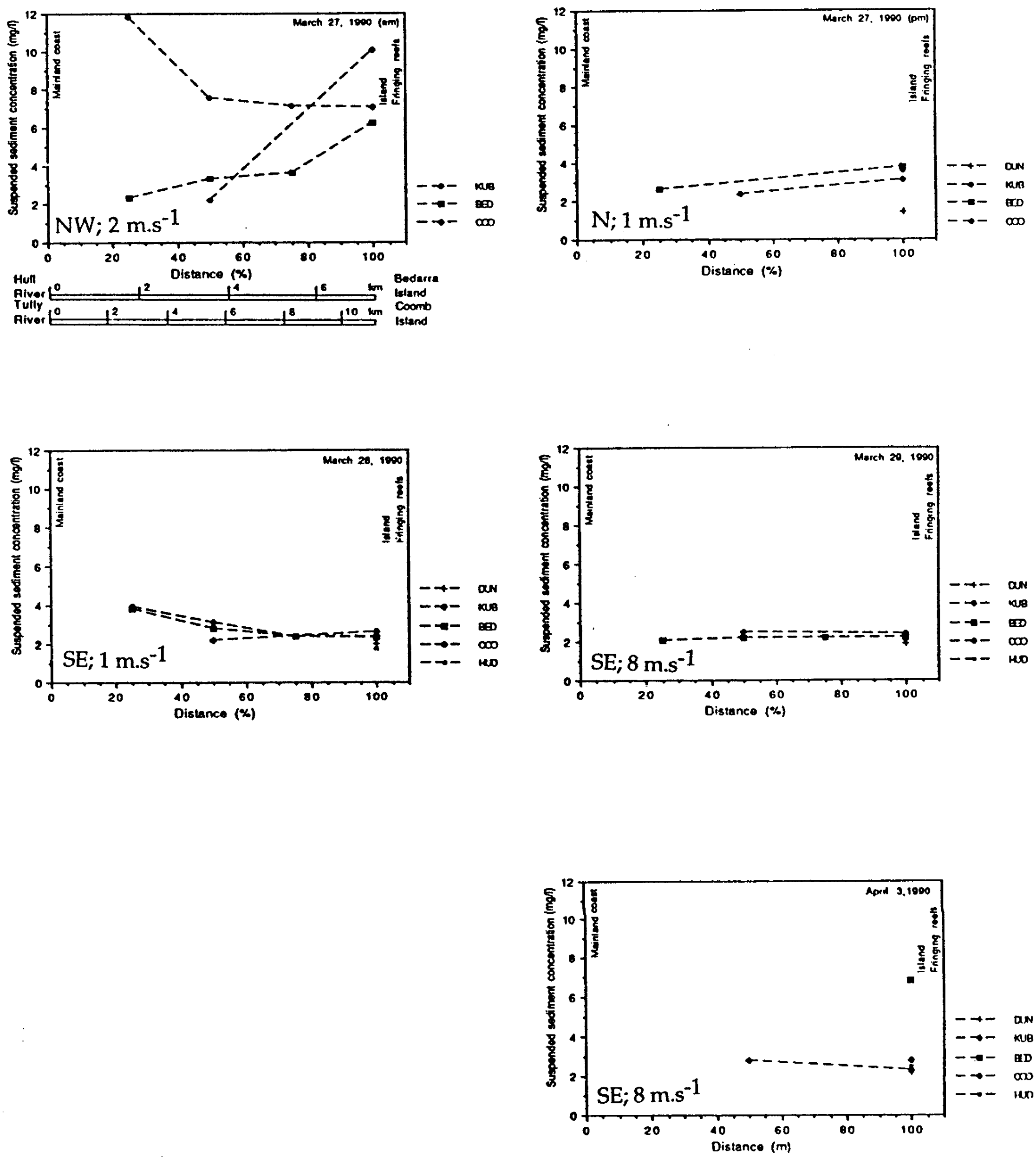


Fig. 5.3.5
Sediment concentration gradients across Rockingham Bay during the 1990 sampling period and wind speed (m.s^{-1}) and direction at the time of sampling; the legend refers to the coral coring sites at which the transects terminate; the legend refers to the coral coring sites at which the transects terminate; distances from the mainland are given in % to systematise the pattern - -> Bedarra = 7.3 km, -> Coombe = 11.2 km.

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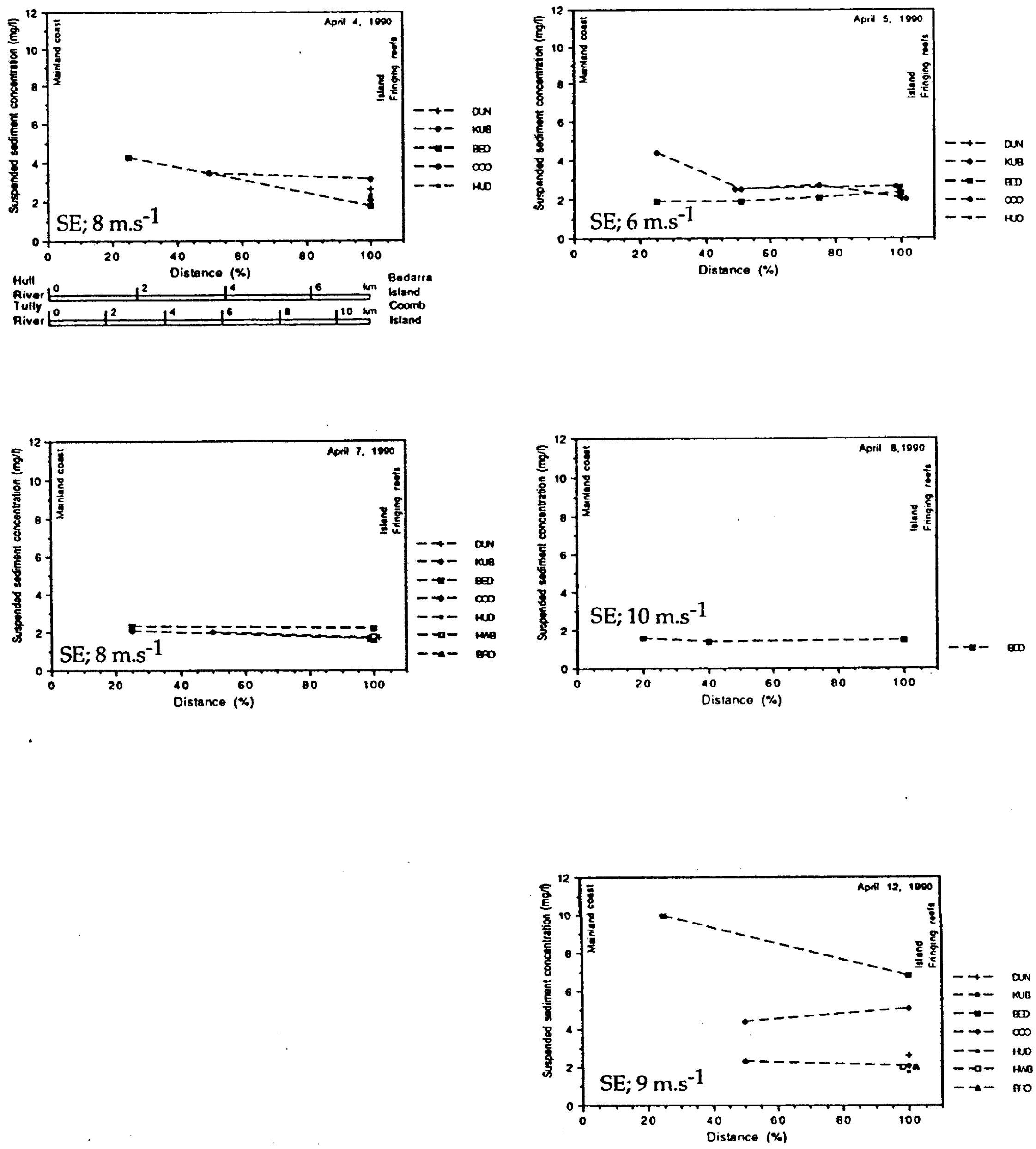


Fig. 5.3.5
Sediment concentration gradients across Rockingham Bay during the 1990 sampling period and wind speed ($m.s^{-1}$) and direction at the time of sampling; the legend refers to the coral coring sites at which the transects terminate; the legend refers to the coral coring sites at which the transects terminate; distances from the mainland are given in % to systematise the pattern - -> Bedarra = 7.3 km, -> Coombe = 11.2 km.

sediment to the waters of Rockingham Bay (cf. 128 cumec event of 8.3.1988 (Fig. 5.3.1)). Prior to this date, floating debris (eg. logs etc.) was observed drifting to the north of the Tully River mouth, consistent with the observed direction of plume movement. However, on the morning of March 29th a northward-moving front, demarcated by drift logs and other debris, was observed between Hudson and Coomb Islands. At this time, suspended sediment concentration at Hudson Island was 2.5 $mg.L^{-1}$ (c. 80 % higher than the background level), higher than at any other of the island sites. The presence of this front, with high turbidity waters to the south, and the relatively high SSC at Hudson Island suggest that this water body may have been due to a somewhat dissipated northward-moving Herbert River sediment plume. This was the only occasion on which there was any evidence of Herbert River waters in the vicinity of Family Group Islands.

A flood peak of 570 cumecs on April 2nd, 1990 was associated with a peak SSC of 64 $mg.L^{-1}$ which occurred on March 30th (Fig. 5.3.3). Sampling of Rockingham Bay waters was undertaken on April 3, 4, 5, 7 and 8th, 1990. An overflight of Rockingham Bay, on the path illustrated in Fig. 5.1.2, was carried out between 13.00 and 13.30 hrs on 3.4.1990 to determine the spatial pattern of river plume movement. At the time of this flight Q was c. 350 cumecs and SSC about 19 $mg.L^{-1}$, 42 % and 57 % respectively of that at the time of the previous flight and 61 % and 18 % of the respective maxima recorded during the event. On the morning of 3.4.1990 (08.00), SSC at Coomb, Bedarra and Kumboola Islands were 2.8, 6.8 and 2.3 $mg.L^{-1}$ respectively. The high SSC recorded at Bedarra Island is entirely inconsistent with all other SSCs recorded in Rockingham Bay at this time and there is no explanation for it. The high mean value for the Coomb, Bedarra and Kumboola Island sites on 3.4.1990 (Fig. 5.3.3) is strongly biased by this outlying value. The apparent relationship between streamflow and SSC at islands sites for the period April 3rd to April 7th is considered to be spurious.

Although the stage of the tide was similar to that on the previous flight, wind conditions differed markedly. There was a 10 $m.s^{-1}$ wind from the southeast (Fitzroy Island data) whereas on the previous flight it was calm. Thus, differences in plume characteristics may be due to both variation in river discharge and sediment concentration and wind effects on bottom sediment resuspension and the direction of plume movement.

Sediment plume distribution at this time is shown in Fig. 5.3.6 and had the following characteristics:-

(i) The high turbidity Murray River plume, of very limited spatial extent, extended slightly southward of the river mouth to a maximum distance of only c. 500 m offshore (Plate 5.7).

(ii) The extensive, low turbidity Tully River plume was moving in a northward direction, largely confined to the mainland coast (Plate 5.8 and 5.9). The width of this plume was at its maximum (c. 1.2 km) immediately offshore from the river mouth, and decreased to about 750 m wide where it passed Tam O'Shanter Point.

(iii) The sediment plume from the Hull River was of high turbidity, but confined close inshore in the immediate vicinity of the river mouth (Plate 5.9).

(iv) There appeared to be little sediment in waters in the vicinity of the Family Group Islands (Plate 5.10).

(v) There was no evidence of a sediment plume, derived from the Herbert River, moving either northward through the Hinchinbrook Channel or around the seaward side of Hinchinbrook Island.

(vi) The presence of an east-west front across Rockingham Bay, in the vicinity of Bedarra Island, with higher turbidity to the north confirmed the importance of tidal fronts in recirculating diluted river plumes through nearshore waters from which the river plume proper is absent.

(vii) The limitation of the sediment plume to within about 1 km of the coast (Plate 5.9) and the clarity of the water at Coomb Island (Plate 5.10) is noteworthy, given that a peak river discharge of 570 cumecs occurred on the previous day.

On 3.4.1990 (07.30 - 08.30) water samples were obtained, with one exception, from island sites only. With the exception of the site at Bedarra Island (6.8 mg.L^{-1}) sediment concentrations were in the range 2.0 to 3.0 mg.L^{-1}. The SSC observed at Bedarra on this occasion is very high given that the plume was observed to be confined close to the coast at the time of sampling, an observation confirmed during the flight which took place only six hours later. This high SSC is not explained by tidal influences, wave resuspension or by rainfall as observed on the mainland.

On 4.4.1990, SSC was 4.2 mg.L^{-1} offshore from the Hull River mouth. At island sites the sediment concentration at Kumboola was the highest (3.1 mg.L^{-1}), with the remainder in the range 1.8 - 2.6 mg.L^{-1}. The mean concentration at Kumboola, Bedarra and Coomb Is. was 2.3 mg.L^{-1} (Fig. 5.3.3). The highest SSC at island sites on 5.4.1990 was 2.2 mg.L^{-1} at Bedarra Island with other island sites clustered in the range 1.6 - 1.7 mg.L^{-1}. The mean SSC at Kumboola, Bedarra and Coomb Is. was again 2.3 mg.L^{-1}.

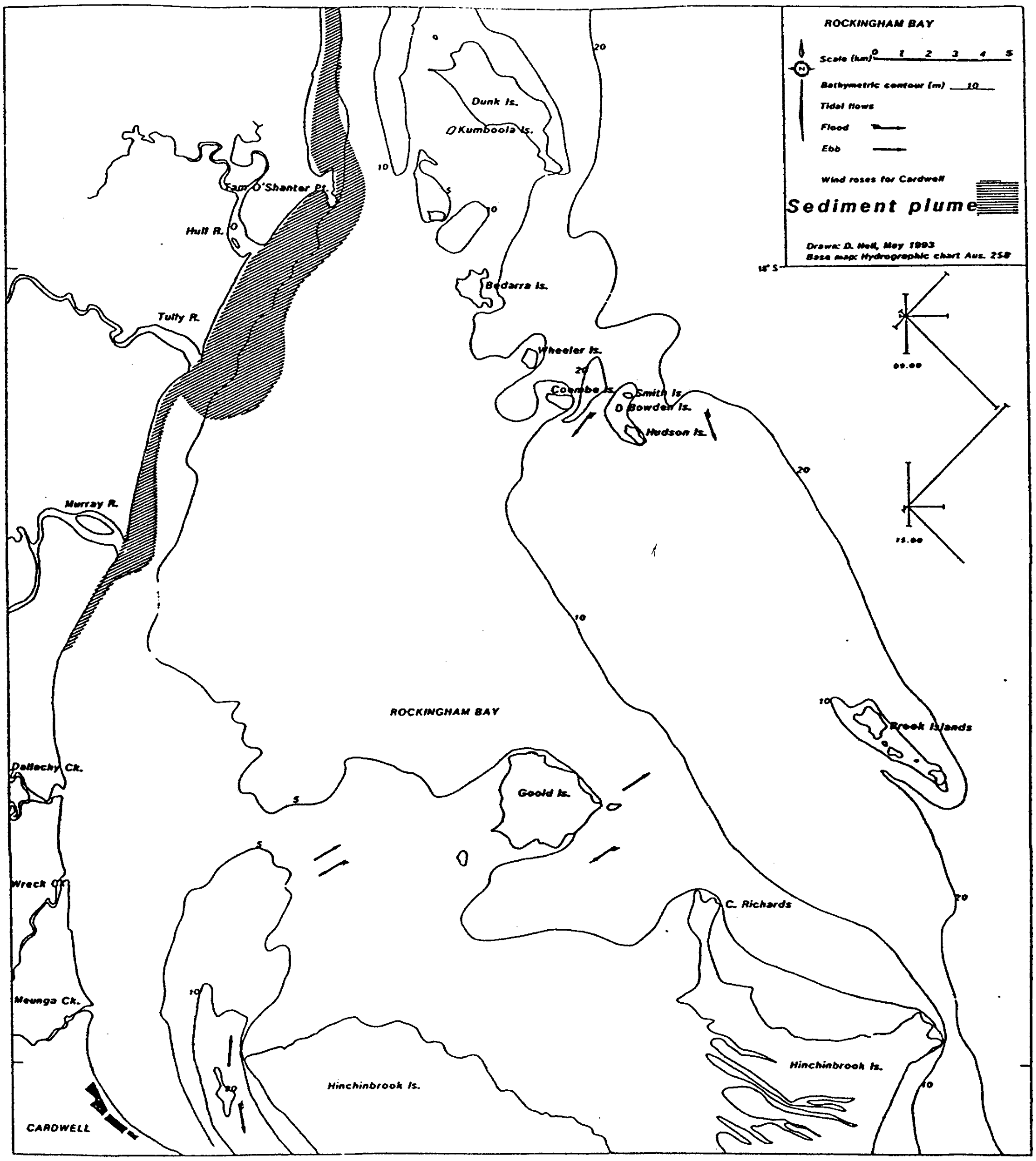


Fig. 5.3.6
Sediment plume distribution in Rockingham Bay, 3.4.1990; mapped from oblique air photography.

Plate 5.7
Sediment plume distribution at the Murray River mouth, 3.4.1990; -> E.

Plate 5.8
Sediment plume distribution in western Rockingham Bay, 3.4.1990; Tully River in centre background; note: extent of plume to south of river mouth, northward plume movement confined to nearshore; -> NW.

Plate 5.9
Sediment plume distribution in western Rockingham Bay, 3.4.1990; Tully River visible in right background, Tam O'Shanter Point centre right; note: plume confined to nearshore; -> SSW.

Plate 5.10
Water clarity in eastern Rockingham Bay, 3.4.1990; Coomb Island in foreground, Smith, Bowden and Hudson in right background; note: high water clarity, fringing reef visibility, dark areas are cloud shadow; -> ESE.

Samples were obtained only on the transect from Hull River to Bedarra on the April 8th, 1990 the SSC at Bedarra being 1.4 $mg.L^{-1}$. The pattern over this period is one of declining sediment concentrations as river discharge and sediment concentration decline and the sediment plume in Rockingham Bay disperses. A final sampling of Rockingham Bay waters was carried out on April 12th, following the discharge peak of 313 cumecs on April 11th. Sampling was concentrated on island sites, and SSCs at Kumboola and Bedarra Islands were 5.1 and 6.8 $mg.L^{-1}$, respectively. Sediment concentrations at the other island sites were clustered in range 1.8 - 2.6 $mg.L^{-1}$. The mean concentration at Kumboola, Bedarra and Coomb Is. was 4.7 $mg.L^{-1}$ (Fig. 5.3.3). The sediment plume was moving northward along the coast under the influence of southeasterly winds which had blown consistently since April 1st. High SSCs at nearshore island sites are attributed to bottom sediment resuspension.

A summary of the suspended sediment concentrations at island sites in Rockingham Bay during the 1990 sampling period is given in Table 5.3.2. Comparison with the mean SSC at Bedarra and at Coomb Islands for the 1988 sampling period (Table 5.3.1) shows that there is little difference between the mean SSCs for the two periods of strongly contrasting streamflow conditions. The maximum SSC recorded at Bedarra Island during the large flood of 1990 is no greater than the maximum recorded there while the Tully River was at baseflow in 1987-1988.

Site	n	mean ($mg.L^{-1}$)	std. dev.	c.v.	minimum	maximum
Brook Is.	2	1.8	0.29	16.6	1.6	2.0
Hudson Is.	7	2.1	0.40	19.1	1.6	2.6
Coomb Is.	9	2.9	1.68	58.7	1.6	7.0
Bedarra Is.	10	3.6	2.20	61.2	1.4	6.8
KumboolaIs	9	3.6	2.58	70.6	1.7	10.0
Dunk Is	8	2.0	0.41	20.0	1.4	2.6

Table 5.3.2
Descriptive statistics of suspended sediment concentrations in Rockingham Bay waters adjacent to fringing reefs on offshore islands (coral core sites; 1990 data).

These results show clearly the tendency of the Tully River sediment plume to move towards the northeast. Evidence of the dissipation of the plume to the north is apparent in the relatively low SSCs recorded at the Dunk Island site. Consistently low SSCs at Hudson Island suggest that relatively little Tully River water moved in this direction during the sampling period. Although only two samples were obtained from Brook Islands, the low sediment concentrations measured tend to confirm the observations from aerial surveys that a coherent Herbert River sediment plume had not extended that far northward.

The highest sediment concentrations recorded at island sites in Rockingham Bay occurred on 27.3.1990 in association with the 24.3.1990 flood peak. A strong relationship between both discharge and sediment concentration in the Tully River and sediment concentrations at island sites is expected and, from the data presented in Fig. 5.3.3, appears to be the case. However, from the limited data available it is not possible to ascertain the exact nature of the relationship. In particular the peak sediment concentration at the island sites is unknown. However, on the basis of both airborne and seaborne observations, it is likely that the maximum concentrations actually measured are lower than those observed during the 25.3.1990 flight. It seems likely that SSC in excess of 10 $mg.L^{-1}$ was maintained, at least at the Kumboola and Bedarra Island sites, for the period 25.3.1990 to 26.3.1990. Weather conditions prevented more frequent observations by air (low cloud, rain). Nor is it possible, in the absence of profiles of sediment concentrations in the bathymetric column, to determine the extent to which declining sediment concentrations in the surface waters are due to mixing in the water column, deposition within Rockingham Bay or transport and subsequent deposition offshore. As a result, sediment concentration/duration relationships in relation to corals at the fringing reef sites are unknown.

Mineralogy of suspended sediments in Rockingham Bay: As in the case of the river samples, XRD diffractograms were influenced by the sediment mass on the filter paper. However, XRD analyses on suspended sediment samples from Rockingham Bay waters at Kumboola, Bedarra and Coomb Islands indicate that the suspended sediment in Rockingham Bay is mineralogically similar to that in the Tully River, dominated by kaolin.

5.3.2.2 *Composition of Rockingham Bay waters:*

The major control over the spatial distribution of the major and minor seawater constituents for which determinations were made is the volume of freshwater influx to Rockingham Bay during the sampling period. Table 5.3.3 lists the mean concentrations of these elements for observations on 29.3.1990, 5.4.1990, 7.4.1990 and 12.4.1990. A breakdown by sites in inshore areas of the bay and at island sites is also given, along with concentrations recorded in river waters during the sampling period, and average values for ocean waters (from Goldberg, 1963) for purposes of comparison.

	Rockingham Bay			River	Ocean
Constituent	All sites (ppm)	Inshore sites only (ppm)	Island sites only (ppm)	samples (ppm)	waters (ppm)
Total N*; $\bar{x}$	0.2	0.15	0.23	0.36	0.5
s.d.	0.18	0.15	0.20	0.16	
min.	0.0	0.0	0.0	.10	
max.	0.62	0.43	0.62	0.95	
n	38	16	22	37	
Si; $\bar{x}$	0.54	0.72	0.40	1.55	3
s.d.	0.56	0.68	0.42	1.07	
min.	0.02	0.07	0.02	0.01	
max.	2.54	2.54	1.92	3.99	
n	38	16	22	37	
Cl; $\bar{x}$	9 116	7 666	10 104	4.30	19 000
s.d.	3 240	3 271	2 887	1.32	
min.	1 102	1 102	3 870	0.58	
max.	15 425	14 850	15 425	8.37	
n	37	15	22	37	
SO_4; $\bar{x}$	1 521.7	1 284.0	1 694.5	1.0	885 as S
s.d.	621.7	586.8	600.6	0.28	(2 550 as SO_4)
min.	433.0	433.0	780.0	0.13	
max.	2 776.0	2 428.0	2 776.0	1.72	
n	38	16	22	37	
Mg; $\bar{x}$	390.5	352.6	418.1	0.54	1 350
s.d.	194.1	197.8	191.1	0.15	
min.	81.5	81.5	182.5	0.16	
max.	978.0	825.0	978.0	0.87	
n	38	16	22	37	
Ca; $\bar{x}$	133.8	122.3	142.2	0.91	400
s.d.	65.9	69.0	63.8	0.26	
min.	27.5	27.5	59.5	0.2	
max.	330.0	285.0	330.0	1.33	
n	38	16	22	37	
K; $\bar{x}$	137.3	125.6	145.8	1.10	380
s.d.	67.3	69.8	65.9	0.24	
min.	29.4	29.4	66.6	0.19	
max.	338	298	338	1.43	
n	38	16	22	37	
Na; $\bar{x}$	3516	2897	3966	3.10	10 500
s.d.	1648	12856	1761	1.01	
min.	642	642	1180	0.51	
max.	8400	5575	8400	5.45	
n	38	16	22	37	

Continued over

	All sites	Inshore	Island	River	Ocean
Sr; $\bar{X}$	4.03	3.83	4.18	n.d.	8
s.d.	1.31	1.09	1.45		
min.	1.05	1.05	1.21		
max.	7.26	5.4	7.26		
n	38	16	22		

Table 5.3.3
Major and minor constituent elements of seawater in Rockingham Bay for observations on 29.3.1990, 5.4.1990, 7.4.1990 and 12.4.1990, for sites in the bay and at offshore islands, with concentrations in river waters and average values for ocean waters (from Goldberg, 1963) for comparison (n.d. = not detectable). * - determinations on filtrates only; particulate concentrations not determined.

Concentrations of Na, Cl and Mg indicate that surface water salinity in Rockingham Bay did not exceed 27.5 ‰ during the sampling period. For the 22 observations at island sites, the mean salinity was 13 ‰. The minimum salinity recorded at the island sites (at Bedarra Island) was 3.8 ‰ and the mean of four observations at this site (29.3.1990, 5.4.1990, 7.4.1990, and 12.4.1990) was 9.8 ‰. At Kumboola Island the minimum was 6.8 ‰ with a mean of 10.9 ‰. Lower salinities occurred at both of these sites for observations on 5.4.1990 and 7.4.1990 than occurred on the 29.3.1990, four days after the flood peak. In Rockingham Bay the average of 16 observations between 29.3.1990 and 12.4.1990 was 9.6 ‰ , with a minimum of 2.1 ‰ in the western bay, considerably lower than the 50% dilution by freshwater reported for Rockingham Bay by Wolanski and and van Senden (1983). Throughout the sampling period (29.3.1990 to 12.4.1990) salinities continued to decline, in spite of decreasing fluvial inputs, and the area of minimum salinity tended to move northward.

Comparing the concentrations of both Total N and Si for river waters, bay waters and average ocean waters shows that, for these two elements, both river and bay waters have lower concentrations than the average ocean water. It seems likely that global average water quality is simply not representative of nearshore waters in the GBR Lagoon.

In spite of the high degree of variability in all parameters, some general observations can be made. Nitrogen concentrations in both the Tully River and Rockingham Bay were generally lower than published ocean water average values. Although concentrations in river waters were higher than in Rockingham Bay, there was not a consistent concentration gradient across the bay. This is shown by the higher values at island sites than at inshore sites (Table 5.3.3). Elevated N concentrations at island sites could result from bottom sediment resuspension (Alongi, 1989) and island runoff (Littler *et al.*, 1991). All other elements show a consistent concentration gradient, with Si declining seaward and Cl, SO_4, Mg, Ca, K, Na and Sr increasing seaward, as expected given the relative concentrations in river water and sea water.

5.4 *DISCUSSION.*

5.4.1 Sediment plume movement:

The pattern of Tully River plume movement in Rockingham Bay during the 1988 and 1990 wet seasons is consistent with the geostrophic effects (Wolanski and van Senden, 1983; Roberts and Murray, 1983) and the wind climate of the region (Chapter 2.2.1). At 35 hours after the flood peak, and at Q of c. 830 cumecs, the intersection of the plume with Bedarra Island was 1 km north of the river mouth and 10 km to the east of it. Fig. 5.4.1 shows that, during the high stream flow period between March 20th and March 26th, 1993 (Fig. 5.3.3), there was little wind effect on the Tully River plume. Winds during this period were generally light and strongly variable in direction as cyclone *Ivor* continued to move southward. Plume movement was dominated by the geostrophic longshore current. SSC at Kumboola Island on March 27th was determined by the characteristics of the sediment plume, falling rapidly as stream flow decreased.

On April 3rd, 1990 (9 days after the earlier flight), with Q at c. 350 cumecs, the plume reached <2 km offshore at 7 km north of the river mouth. Movement of the sediment plume generated by the high stream flows from March 30th onward (Fig. 5.3.3) is strongly influenced by the onset of consistent southeasterly winds after the influence of *Ivor* ceased (Fig. 5.4.1), which persisted until April 16th. Wind velocities were generally in the range 8 - 10 $m.s^{-1}$ during this period and the SSC at Kumboola Island was in the 2 - 3 $mg.L^{-1}$ range.

The general pattern of plume movement during the period of observation is to the northeast in the period immediately following the peak discharge, bathing fringing reefs of the northern Family Group islands in high turbidity water. Some, relatively diluted, river waters may reach the southern Family Group islands as a result of tidal circulation. Subsequently the plume was confined close to the coast by the combination of onshore winds, a lower discharge volume and a weaker geostrophic current.

The movement of the Tully River sediment plume is similar to that during June, 1961, mapped from aerial photographs (Fig. 5.1.1). It is contrary to the longshore drift of sand-sized sediments from the Hull, Tully, and Murray Rivers suggested by Pringle (1986). It is also differs from the direction of movement following the February, 1986 flood (cyclone *Winifred*) when the plume passed to the south of Coomb Island (Hopley, 1987, pers. comm.). Plume movement at that time was probably influenced by the strong winds from the northern and western quadrants which followed the passage of cyclone *Winifred* (Walker and Reardon, 1986; Marcum, 1986).

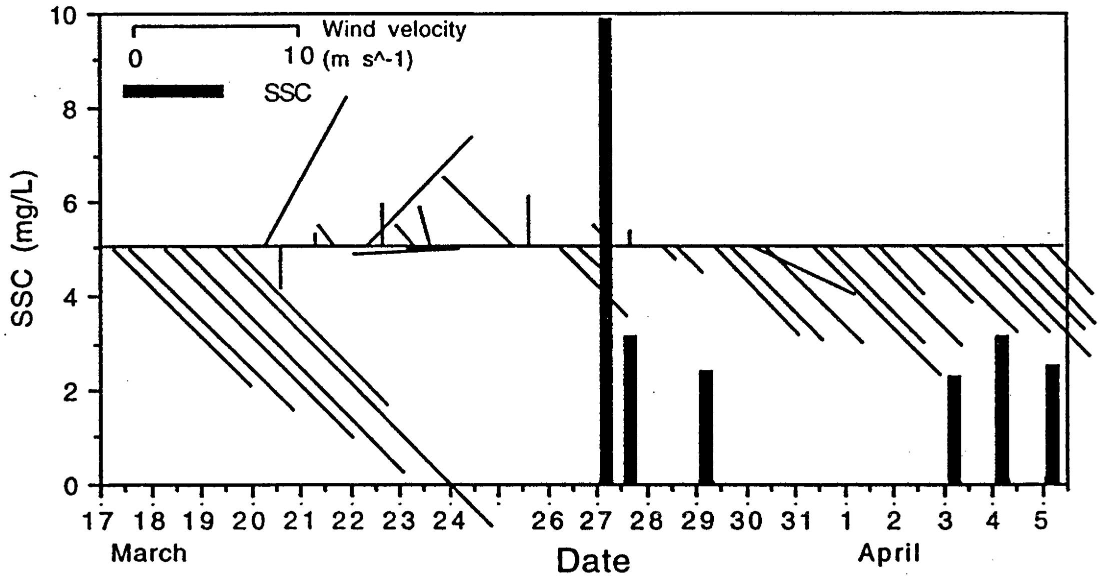


Fig. 5.4.1
Wind ray diagram for Fitzroy Island (Aust. Bur. Met. data; 09.00 and 15.00) prior to and during aerial observations of the Tully River sediment plume in March and April, 1990. Suspended sediment concentrations for six observations at Kumboola Island are also shown.

Wind directions at the times of ten Tully River floods with peak daily flows > 40 000 ML during the period 1987 - 1991 are shown in Fig. 5.4.2 (a-j). In all cases except one (c), winds were in the southeast quadrant prior to the flood. Winds during these events can be subjectively allocated to four categories:

(i) Winds exclusively in the southeast quadrant (cases (e) and (g)).

(ii) Winds predominantly in the southeast quadrant with one or two north and northeasterly observations (cases (a), (b) and (d)).

(iii) Winds predominantly in the southeast quadrant, with several north and northeasterly observations (cases (c), (h) and (j)).

(iv) A substantial proportion of winds from quadrants other than the southeast (cases (f) and (i)).

These results suggest that, for perhaps 4 in 5 flood events in the Tully River, winds from the southeast are the dominant influence on sediment plume movement throughout the event and the plume is unlikely to reach island sites. In some events, for example March, 1990 (Fig. 5.4.1) and cases (f) and (i) in Fig. 5.4.2, northerly winds have a significant effect.

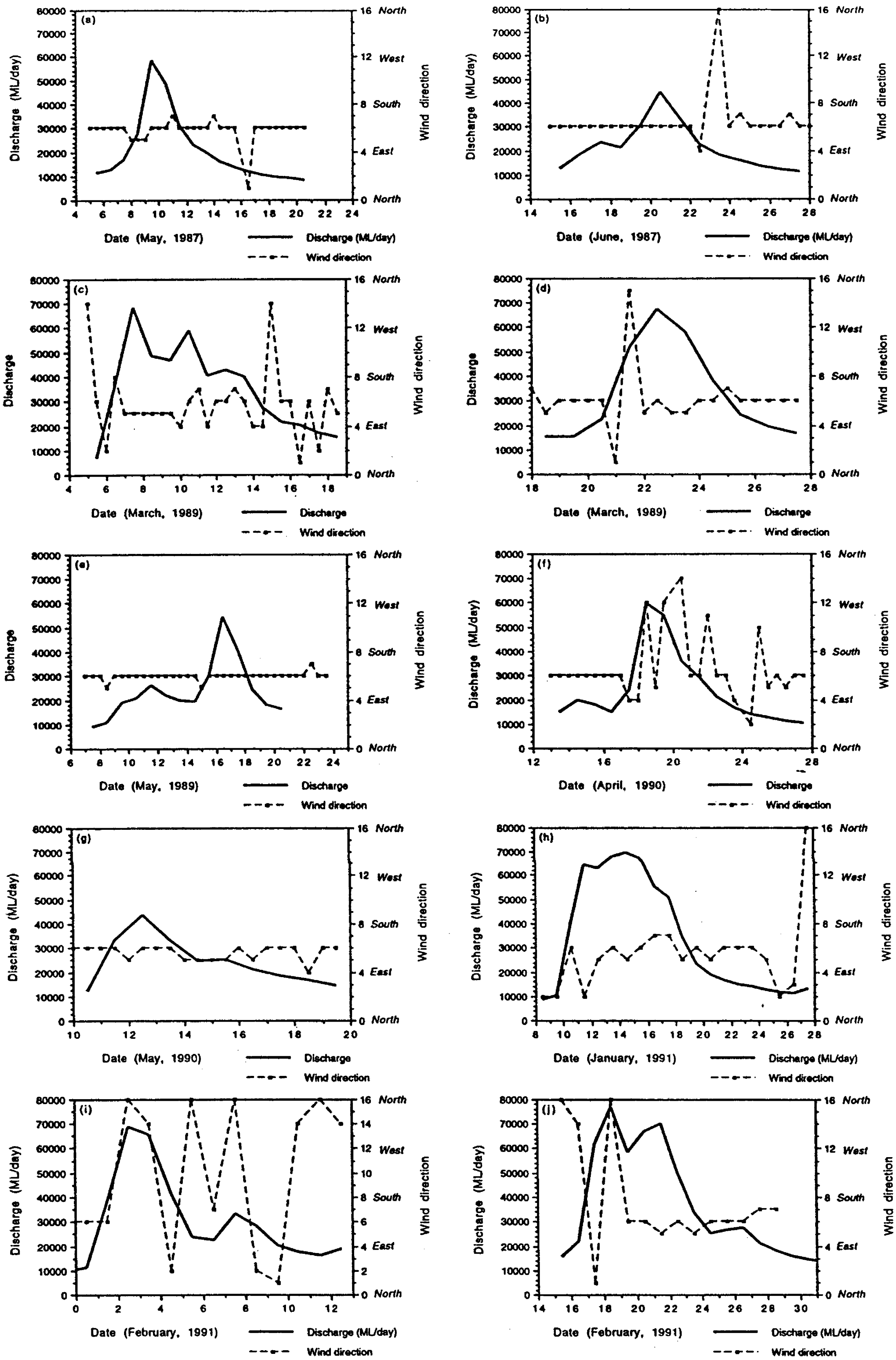


Fig. 5.4.2
Wind direction (Fitzroy Is.) and daily streamflow (Tully River) for ten events with peak daily flow > 40 000ML (1987-1991).

The influence of northerly winds, evident during the March, 1990 flood, is most likely to occur early in the wet season (Chapter 2.2.1) or as a cyclone continues on a southerly track. It is confirmed by the documented behaviour of sediment plumes from the Fitzroy River. Under these conditions a more easterly component in sediment plume movement is likely. This has been shown for the Capricorn coast in modelling experiments (BPA, 1979). Persistent southeasterlies maintain the northward movement and a subsequent shift to winds from the north is predicted to generate easterly plume movement. For example, following cyclone *Joy* the initial sediment plume movement from the January, 1991 Fitzroy River flood, the third largest this century, was northward along the coast. Following the flood peak on January 10th, southeasterlies persisted until January 17th, after which time winds from the northwest - northeast quadrant persisted for about a week. Under these conditions, the sediment plume then moved east-southeast and reached Heron Reef, 80 km east of the Fitzroy mouth, on the 23rd of January (O'Neill *et al.*, 1992). By analogy with this pattern, Tully River plumes are also likely to move in an easterly direction, following the passage of a cyclone, as observed by Hopley (1987, pers. comm.) following cyclone *Winifred.*

Plume distribution adjacent to the mainland coast is shown in Plates 5.2 (25.3.1990) and Plate 5.9 (3.4.1990). In the early part of the event, low turbidity, high salinity lagoon waters are trapped adjacent to Tam O'Shanter Point. Nine days later the plume lay along the coast with little evidence of entrappment of lagoonal waters on its landward side. By this time, the turbidity had declined (see below). This pattern is quite similar to that observed for the Burdekin River plume by Wolanski and van Senden (1983; Figs. 3-5)) and has ecological implications for the northern sides of headlands on the east Australian coast, which appear to be protected from both the salinity and turbidity extremes of river plumes and sediment and nutrient resuspension by the prevailing southeasterly winds. While this behaviour is of limited relevance to this study, as all coral core sites are from island sites, similar behaviour was observed by Wolanski and van Senden (1983) for the Burdekin plume in the vicinity of the Palm Group and is elaborated on in greater detail by Wolanski, Pickard and Jupp (1984). Some of the patchiness in the Tully River plume, also described for the Burdekin River plume by Wolanski and van Senden (1983), appears to be related to tidal effects.

In the context of this study, variability in the direction of sediment plume movement demands that sites for the extraction of coral cores should, as far as possible, be located in positions capable of detecting sediment plumes irrespective of their direction of movement. However, the availability of sites is entirely controlled by the location of the fringing reef islands. It is clear from the results of this study and Hopley's (1987) observations that the main area of influence of the Tully river plume may vary from the southern Family Group islands to the mainland coast north of the river mouth. Three general conditions can be inferred:

(i) Movement northward along the mainland coast under strong southeasterly conditions assisted by the geostrophic current.

(ii) Movement toward the northern Family Group islands under the influence of the geostrophic current during light, variable winds.

(iii) Movement toward the southern Family Group islands forced by strong northerly winds and moderated by the geostrophic current.

The first of these is probably the most common. It can be inferred from the Tully River plume movement observed during March, 1990, wind patterns during flood events (Fig. 5.4.2), and the behaviour of the Fitzroy plume during the 1991 flood (O'Neill *et al.*, 1992), that significant changes in the location of plume impact may also occur during the course of an event.

5.4.2 Suspended sediment concentrations:

Patterns of sediment distribution observed in Rockingham Bay during the 1988 and 1990 wet seasons are in general agreement with those observed sedimentologicaly for inner-shelf GBR waters. Suspended sediment concentrations were greatest nearshore adjacent to river mouths and declined offshore. There was little evidence of sediment transport into mid-shelf areas, in agreement with other results from the region (eg. Gagan, Sandstrom and Chivas, 1987; Gagan, Chivas and Johnson, 1989).

The maximum sediment concentrations observed at island sites occurred on the 29.3.1990, in contrast to the minimum salinities which lagged the sediment concentration maximum, by about two weeks (see 5.4.3 below). This may be attributed to two factors. Firstly, to sea surface accumulation of buoyant freshwater runoff in the bay area, while particulate matter settles relatively rapidly through the bathymetric column and, secondly, to the lag of the discharge peak behind the suspended load peak observed in the Tully River.

Given the limitations of the sampling procedure and the frequency of observations it is not possible to adequately disassociate the contributions of wave resuspension and river plume derived sediments in nearshore surface waters. The observation that the highest SSC recorded at Bedarra Island while the Tully River was at baseflow (4.9 $mg.l^{-1}$) is about 70 % of the maximum recorded at that site during the 1990 flood indicates that wave resuspended sediment may be of equal or greater importance for water quality in nearshore waters than direct fluvial inputs. This is particularly the case given that vertical profiles of SSCs associated with sediment plumes have surface water maxima and those associated with wave resuspension have bottom water maxima.

Further evidence of the importance of bottom sediment resuspension comes from the observation that suspended sediment concentrations at island sites are often slightly higher than those at the nearest sampling site landward of them. Table 5.4.1 shows the results of comparisons of paired observations from the 1988 and 1990 wet seasons. There are a number of possible explanations. Entrapping of river plume waters adjacent to the islands (Wolanski, Imberger and Heron, 1984) is unlikely as it was never observed during either aerial or boat surveys. Runoff from the islands is also unlikely as no plume or front associated with island runoff was observed at any site for any of the observations made. The most likely explanation is wave resuspension of bottom sediments in the very shallow waters immediately adjacent to these islands. The SSC increase is greatest at the Kumboola Island site (35%) which has extensive shallow water areas adjacent, and least at the Coomb Island site (-1%) which is surrounded by relatively deep water. Similarly, the difference between variability at shallow water island sites (Kumboola, Bedarra) and the adjacent site is much greater than is the case for the deep water island site (Coomb) and its adjacent site.

Island	Kumboola		Bedarra		Coomb	
Site	At island	Adjacent to island	At island	Adjacent to island	At island	Adjacent to island
n	9	9	17	17	9	9
x ($mg.l^{-1}$)	3.66	2.70	2.71	2.53	3.02	3.05
s.d.	2.56	0.76	1.25	0.88	1.77	1.67
c.v. (%)	70	28	46	35	58	55
% increase at island site	35		7		-1	
Error probability (paired t-test)	0.15		0.16		0.44	

Table 5.4.1
Comparison of suspended sediment concentrations at island sampling sites with sites immediately to landward.

The field evidence from the 1988 and 1990 wet seasons indicates that bottom sediment resuspension is an important source of the suspended sediments in Rockingham Bay. This is particularly the case in the vicinity of the islands where shallow waters increase resuspension rates. The magnitude of the 1990 flood, in combination with the extent of land use change which had occurred by 1990, suggests that river derived SSCs recorded at the coral core sites are likely to be as great as any experienced in the past 65 years. Sampling of bay waters could not be undertaken during the strongest winds of the sampling period (if forecast winds were > 25 knots, sampling was not usually contemplated) and at no time during the sampling period was an extreme wind event experienced. However, gale force winds (> 33 knots, c. 18 $m.s^{-1}$) are uncommon in the study area. At Fitzroy Island which has a high frequency of strong wind occurrence (Fig. 2.2.6) gales occur on only one day in every 230 (20 years of record) and at Cardwell on only one day in 1 400 (31 years of record; Aust. Bur. Met. data). It follows that much greater sediment concentrations, due to either wind resuspension or river discharges, than were experienced during the sampling period are uncommon. It seems likely that this pattern also applies to the duration of high sediment concentrations.

The seasonal pattern of high frequency of winds capable of resuspending bottom sediments overlaps the period during which high stream flows occur (Fig. 5.4.3) in the March - May period. As a result, it is not possible to fully discriminate between fluvial and bottom sediment sources by analysing coral skeleton formed at different times of the year.

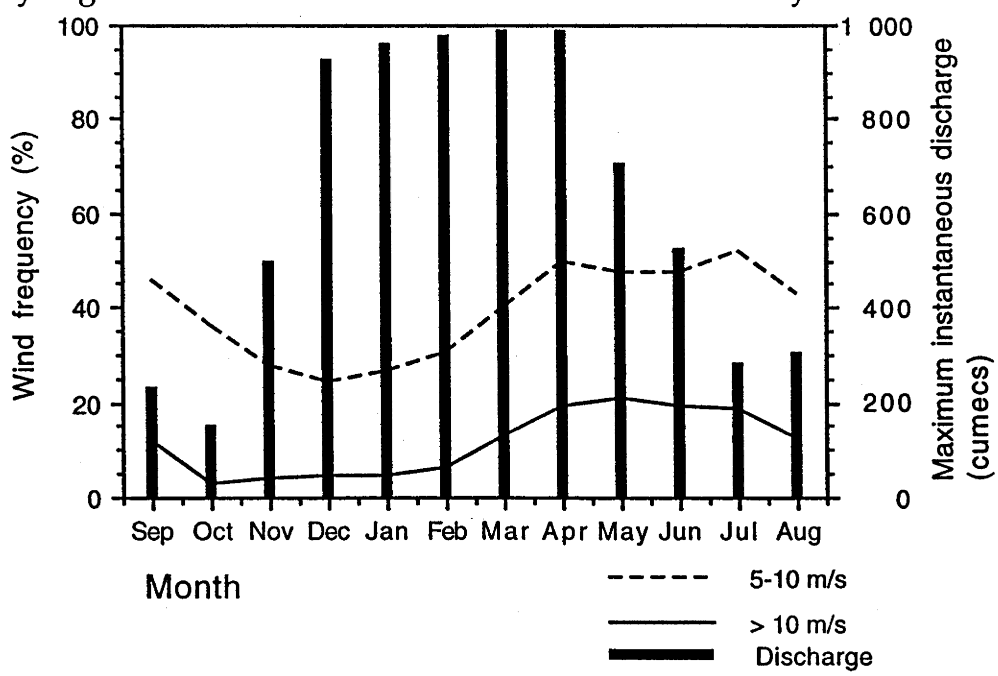


Fig. 5.4.3
Seasonal relationship between strong winds at Fitzroy Island and the maximum instantaneous discharge recorded in the Tully River.

The data suggest that the fluvial sediment signal at the island (ie. coral core) sites will generally be indistinguishable from bottom resuspension-induced sediment concentrations.

5.4.3 Salinity:

During the 1990 wet season, surface water salinities were much lower throughout the Rockingham Bay area than observed by Wolanski and van Senden (1983). Salinities observed by these workers were in response to flooding in the Burdekin River, their study was a spatially extensive one and detailed surveys within Rockingham Bay were not undertaken. Tully River discharge at the time of Wolanski and van Senden's initial survey was c. 370 cumecs and had been greater than this level for 13 days, peaking at 955 cumecs 10 days earlier. It seems likely, therefore, that much lower salinities occurred in Rockingham Bay at this time, undetected by the sampling strategy used by Wolanski and van Senden (1983).

The northward movement of the minimum salinity during the sampling period is consistent with the dynamics of plume movement. However, the continued decrease in surface water salinity during the sampling period while rainfall and streamflow were decreasing is indicative of poor mixing and accumulation of low-salinity river waters in the bay. Although salinities at Hudson, Coomb and Dunk Islands had started to increase by the 12.4.1990 observation, at Bedarra and Kumboola Islands they were still decreasing. With the exception of one observation at Dunk Island (29.3.1990; 28.0 ‰) salinities at island sites did not exceed 21 ‰ during the sampling period. The mean at Kumboola Island was 10.9 ‰. Although these values refer to surface waters only, the very low salinities observed and their duration (> 2 weeks) are a likely contributing factor to the relative paucity of scleractinian corals adjacent to the Family Group islands. Hopley (1982) notes that the normal tolerance range of corals and coralline algae is 30 to 40 ‰.

It seems likely that both the deviation from background concentrations and the duration of such deviations is greater for salinity changes than for changes in sediment concentrations due to fluvial outputs. Consequently, salinity effects rather than fluvial sedimentation effects are the more likely fluvial influence on coral viability in Rockingham Bay.

5.4.4 Water chemistry:

Total N levels at island sites are about 45% greater than at adjacent sites within Rockingham Bay. This is an enhancement of the pattern for SSC (Table 5.4.1). The pattern of Si concentrations across Rockingham Bay during March/April, 1990 is one of maximum concentrations in river waters declining offshore to reach minimum levels in the vicinity of the offshore islands. It appears that, unlike the distribution of SSC and Total N, there is no significant input of Si to surface waters as a result of wave resuspension, in agreement with the results of Ullman and Sandstrom (1987), and the distribution of Si appears to be largely controlled by river plume dynamics. Net fluxes of Si between sediments and overlying waters may exhibit a seasonal pattern in coral reef waters (eg. Johannes, Wiebe and Crossland, 1983), although D'Elia and Wiebe (1990) suggest that they will be small to negligible. Ullman and Sandstrom's (1987) results indicate that this is also the case for nearshore waters dominated by terrigenous sedimentation.

The strong, inverse correlation of Si with salinity is in agreement with reported relationships for estuarine and nearshore waters generally (Boyle *et al.*, 1974), and for nearshore GBR waters specifically (Walker and O'Donnell, 1981). The strong onshore - offshore Si gradients and high latitudinal variability reported by Furnas (1991b) reflect this relationship.

Although Si may be a limiting nutrient for taxa such as diatoms, silicoflagellates, radiolarians and siliceous sponges in coral reef environments (D'Elia and Wiebe, 1990), these organisms are a relatively minor component of coral reefs, dominated as they are by calcareous organisms, and relatively little utilisation of Si takes place in coral reef systems. Walker and O'Donnell (1981) showed that, in both fluvial and marine waters adjacent to the GBR, silicon: phosphate ratios were sufficiently high that Si was not the limiting nutrient for phytoplankton production, confirming Orr's (1933) results from Low Isles.

River plume dynamics also control the distribution of Cl, SO_4, Mg, Ca, K, Na, and Sr, all of which have increasing concentrations with distance offshore. These elements follow a relatively simple pattern controlled by dilution of shelf waters by river water, with no apparent effect of resuspension in the vicinity of offshore islands.

Many of the solutes analysed (Cl, SO_4, Mg, Ca, K) have concentrations linearly related to water salinity (measured as Na concentration) with regression slopes close to zero. This implies that the increase in concentration of these solutes away from the river mouth is controlled by dilution of the river plume.

However, this is not the case for all components of Rockingham Bay waters. Total N, Si, and Sr exhibit higher ratios to Na in waters of low salinity than in those at high salinity. Similarly, SSC:Na ratios are higher at low salinities (Fig. 5.4.4). The break in slope of the relationship between solute and particulate concentrations and salinity occurs at about 10 ‰ as observed by Wolanski and Jones (1981) for the SSC/ salinity relationship in the Burdekin River plume. In this case it was concluded that break in slope implied a significant loss of sediment from the water column adjacent to the river mouth. The linear relationship at higher salinities was interpreted as evidence that, above 10 ‰, no further deposition took place and concentrations were determined by dilution only. Therefore fine sediments could remain in suspension for great distances, eg. as far as the outer reefs. In the case of the Tully River/Rockingham Bay data, the settling of suspended particulates from surface waters appears to continue, even at high salinities. A simple settling model cannot be invoked to explain the similar pattern for Total N, Si, and Sr (Fig. 5.4.4). Pearsons 'r' and Spearmans Rank Correlation Coefficient were used to examine the relationship between SSC and these elements, and between SSC:Na and Tot N:Na, Si:Na and Sr:Na, in order to test the hypothesis that these anomalous patterns were SSC mediated. None of the relationships was significant, suggesting that the behaviour of these elements is independent of sediment dynamics.

5.5 *SUMMARY.*

Tully River sediment plume movement across Rockingham Bay is in accord with the documented role of wind forced, nearshore currents and geostrophic currents, as described by Wolanski and Thompson, 1984. The resultant plume movement may be highly variable affecting the mainland coast under strong southeasterly conditions, the northern Family Group islands under the influence of the geostrophic current and light, variable winds, and the southern Family Group islands during strong northerly winds. The dominant influence on plume movement appears to be the southeasterly wind. The results show that fluvial sediments, which are dominantly kaolin, reach island fringing reefs with concentrations of 2 to > 5 times the background concentration. Sediment plumes may occur during the dry season (Fig. 5.1.1).

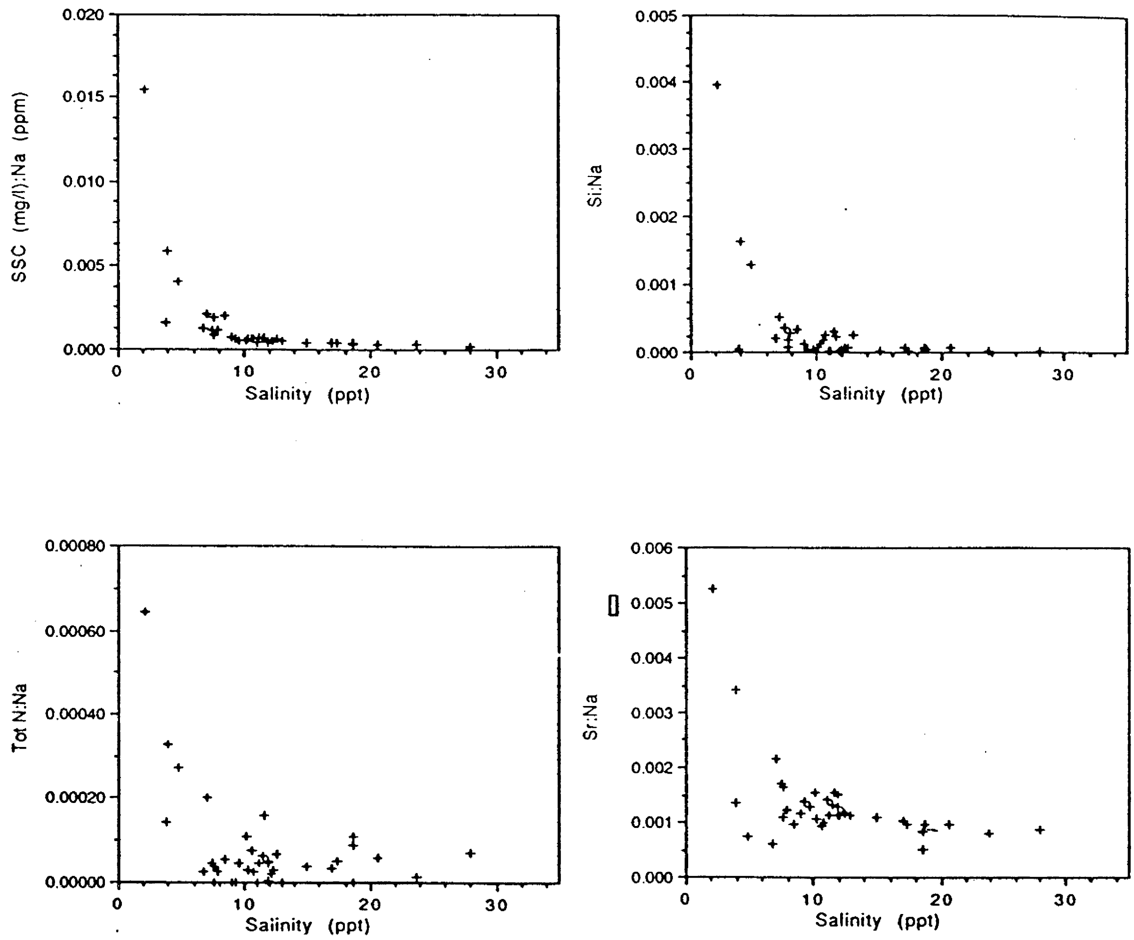


Fig. 5.4.4
Relationship between salinity and the concentration of SSC, Total N, Si, and Sr in Rockingham Bay surface waters.

The direct effect of the plume is likely to occur predominantly in the vicinity of Bedarra, Timana and Kumboola Islands, although its impact on these sites may be of only limited duration, dictated by oceanographic conditions. The effect of salinity depression at these sites is of far greater duration than the elevation of SSC resulting from fluvial inputs. Tidal circulation of river plume waters ensures that other fringing reefs, such as Dunk, Coomb and Hudson Islands are also affected, although at reduced sediment concentrations.

There is evidence of entrappment of oceanic water against the coastline in the vicinity of Kennedy and Lugger Bays and of some recirculation of mid-SSC waters as a result of tidal action.

Evidence of a water body which could be attributed to the movement of the Herbert River plume northward around the eastern side of Hinchinbrook Island was obtained on only one occasion (29.3.1990) when SSC at Hudson Island was higher than at any other island site and about 70 % greater than the postulated background concentration.

Bottom sediment resuspension appears to influence both sediment and nitrogen concentrations, particularly in the vicinity of the offshore islands, to the extent that river-derived sediment concentrations are likely to be indistinguishable from resuspended sediment concentrations.

It appears that there are three patterns of solute and particulate distribution in Rockingham Bay for the parameters analysed. These are:

(i) Concentration maximum occurs in river waters with a decline offshore as mixing takes place, as in the case of Si, which is likely to be of relatively little ecological significance.

(ii) Concentration maximum in river waters with a mixing forced decline offshore and an increase in the vicinity of the offshore islands as a result of bottom sediment resuspension. This pattern applies to SSC and Total N and has implications for coral growth in the vicinity of continental islands and possibly for algal blooms in nearshore waters.

(iii) Concentration minimum in river waters with an increase offshore as mixing takes place. Cl, SO_4, Mg, Ca, K, Na and Sr comply with this pattern.

The marked break in the slope of the relationship between SSC and salinity at 10 ‰, consistent with the results of Wolanski and Jones (1981), is indicative of substantial sediment deposition in the immediate vicinity of the river mouth.

The pattern of sediment plume movement suggests that Kumboola Island is the coral core site most frequently influenced by fluvial inputs. It is also a site of greater than average bottom sediment resuspension. Estimates of the suspended sediment concentration and its frequency of occurrence for differing wind and stream flow conditions, using all available data, are presented in Table 5.5.1.

Conditions	SSC estimate ($mg.L^{-1}$)	Frequency of occurrence (%)
Winds < 5 $m.s^{-1}$ or offshore	1 - <2	50
Onshore winds 5 - 10 $m.s^{-1}$	2 - 4	40
Onshore winds > 10 $m.s^{-1}$	4 - >6	10
Discharge 400 - 600 cumecs	4 - 6	2.8 (0.6 *)
Discharge > 600 cumecs	6 - > 10	1.6 (0.3 *)

Table 5.5.1
Estimates of SSC at Kumboola Island in relation to wind (Fitzroy Is.; Fig. 5.4.3) and stream flow (Tully R.) conditions and their frequency of occurrence (* - estimate corrected for wind forcing of sediment plumes (see Fig. 5.4.2).

The table suggests that some resuspension of bottom sediments at Kumboola Island occurs about 50 % of the time and fluvial sediment plumes about 5 % of the time. However, these estimates assume that all sediment plumes reach Kumboola Island. When the stream flow effect is corrected for wind forcing of sediment plumes, as outlined in Fig. 5.4.2, the frequency of sediment plume impacts at this site is much reduced (by 80 %, values denoted *). Although sediment concentrations from river plumes may be about twice as high as those from bottom sediment resuspension, the bottom sediment resuspension appears to occur more than ten times as often. Comparison of the results presented in Table 5.5.1 with the inferred changes in potential sediment yield (Fig. 4.3.1) suggests that, prior to land use change, the maximum fluvial sediment concentrations would have been similar to those from bottom sediment resuspension for a flood event of similar characteristics.

Relationships between sediments and corals are discussed in Chapter 7.

CHAPTER SIX

THE CORAL FLUORESCENCE RECORD OF TULLY RIVER STREAMFLOW

CONTENTS

6.0	GENERAL INTRODUCTION
6.1	CORAL CORE RETRIEVAL AND PROCESSING
6.2	SKELETAL FLUORESCENCE
6.3	SUMMARY

6.0 *GENERAL INTRODUCTION:*

Massive corals are useful environmental recorders. Knutson *et al.* (1972) and Macintyre and Smith (1974) showed that growth bands, generally as 5 - 15 mm thick high and low density couplets, represent reliable annual series, analagous to tree rings. Variations in coral growth rates have been analysed in relation to suspended sediment concentration (Dodge, *et al.*, 1974), oil and oil dispersants (Dodge, *et al.*, 1984a), light availability and water temperature (Highsmith, 1979). Skeletal geochemistry reflects changes in water chemistry, and sections of coral skeleton were analysed to assess lead pollution (Dodge and Gilbert, 1984; Shen and Boyle, 1987), phosphorus pollution (Dodge *et al.*, 1984b), fallout plutonium (Benninger and Dodge, 1986), concentrations of cadmium (Shen *et al.*, 1987) and other metals (Howard and Brown, 1987) and changes in stable isotope ratios (Druffel, 1982). This chapter examines the usefulness of one environmental recorder in corals, UV fluorescence intensity as a recorder of stream flow in adjacent streams, for reconstructing Tully River stream flows. Such a record of stream flow before instrumental records commenced is essential in putting the sediment yield history from the coral skeleton in its climatic and hydrologic context.

Early research on coral skeletal records used whole colonies from which slabs were cut, destroying the colony. More recently, relatively sophisticated underwater drilling equipment has been used. The locations of coral sampling sites, the methods of obtaining the coral cores and their initial processing are described in Chapter 6.1.

The stream flow record obtained from skeletal fluorescence is described in Chapter 6.2. The nature of the coral fluorescence, methods of obtaining a quantitative fluorescence time series, and the relationship between fluorescence and stream flow in the Tully catchment, and sources of unexplained variance in this relationship are discussed. A summary of the results of this analysis is given in Chapter 6.3.

6.1 CORAL CORE RETRIEVAL AND PROCESSING:

6.1.1 Core retrieval:

Coral heads (*Porites* spp.) suitable for coring were identified at several islands in Rockingham Bay (Fig. 6.1.1). *Porites* spp. are used for these analyses because they grow to a great age (500 to 1 000 years for very large colonies), have a widespread distribution encompassing most of the range of photic zone corals, occur in a wide variety of environments within their range including nearshore turbid waters, have sufficient growth rate to give good chronological resolution, their massive growth form makes them suitable for drilling and yields a continuous time series record, and their skeletal density renders them reasonably easy to drill. This said, not all *Porites* species occur throughout the geographical or environmental range of the genus, some species do not assume the massive growth form, and, in some cases, a variety of growth forms may occur within a species (eg. massive, columnar and encrusting in the case of *P. heronensis*; Veron, 1986).

The islands at which coring sites were located form an arc around the Tully River mouth. Suitable coral heads were found at Dunk (9.6 km from the river mouth; site code - DUN), Kumboola (8.0 km; KUB) Bedarra (7.3 km; BED), Coomb (11.2 km; COO) and Hudson (14.6 km; HUD) Islands (Fig. 6.1.1). A core from Brook Islands (28 km from the river mouth; BRO) had previously been recovered by AIMS. There were no suitable coral heads at Goold Island. The site codes (shown in brackets, eg. (DUN)) are used below.

Coral heads at these sites were cored during an AIMS cruise in April/May, 1988, using a lightweight drilling rig. This rig extracts 93 mm diameter cores in 700 mm sections and > 10 m long (Isdale and Daniel, 1989). The drilling rig, developed by Isdale and Daniel, was built for extraction of long cores from isolated massive coral colonies. It is air powered which minimises the risk of pollution associated with drilling but, due to the available delivery pressures of commercial compressors, has an operating depth limited to about 15 m. For coring shallow water massive corals, it is superior to equipment described by Macintyre (1975), Stearn and Collassin (1979) and Hudson (1981).

Coral head morphology is examined carefully in order to align the drilling axis as closely as possible to the coral growth axis. Multiple cores were extracted from each coral head. Drill holes were closed with a concrete plug and the drilling detritus was cleared from the coral head. In this way the coral core is obtained without destruction of the colony.

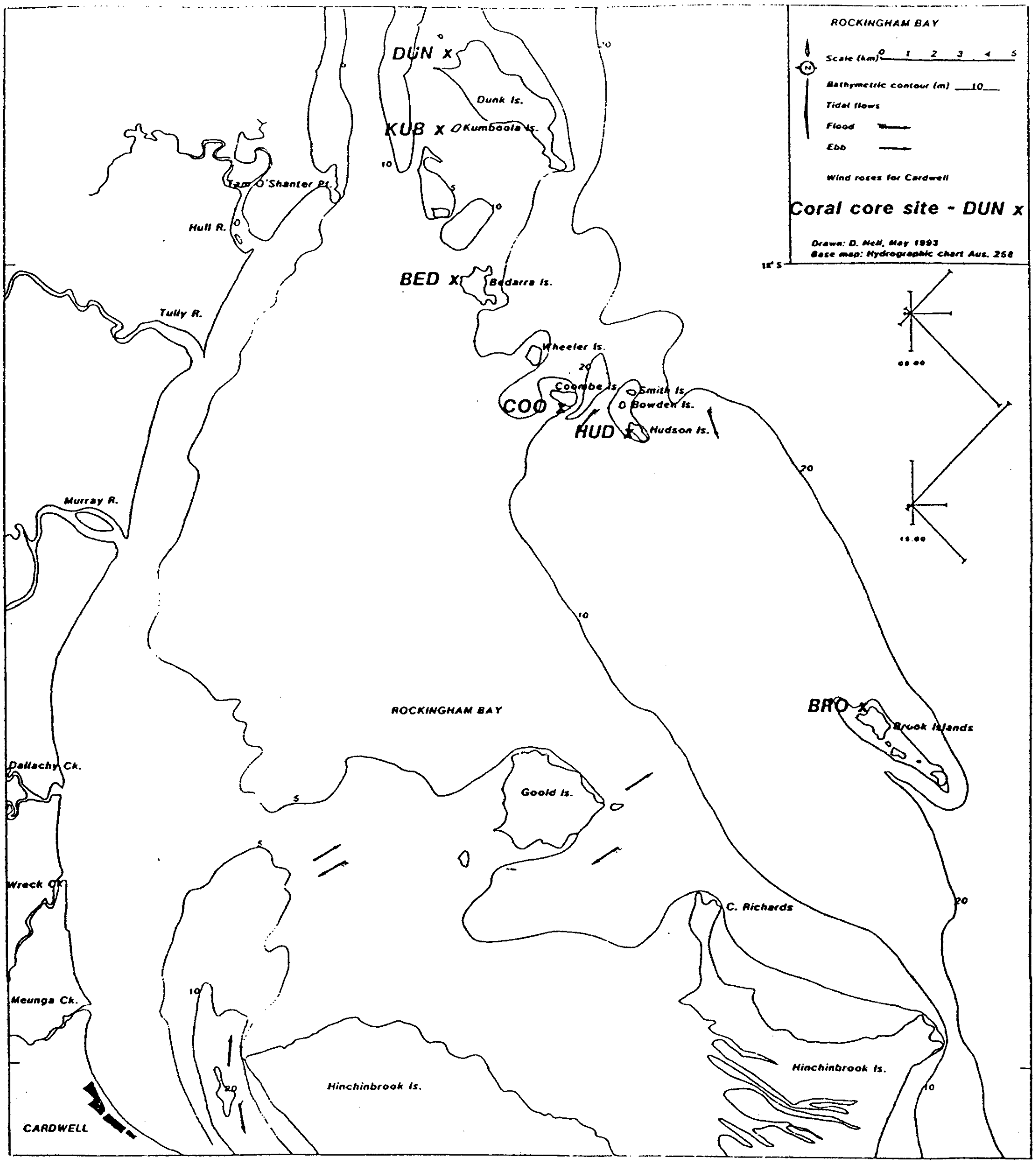


Fig. 6.1.1
Location of coral coring sites in Rockingham Bay.

6.1.2 Core processing:

On returning to the laboratory, the best core from each coral head sampled was selected for further analysis on the basis of minimal evidence of damage by boring organisms and the best alignment of the core with the growth axis of the coral. Summary descriptions of each of the selected cores are given in Table 6.1.1. In a number of cases the core is longer than the height of the coral head, as a result of sediment accumulation around the base of the coral head and/or settling of the increasingly heavy coral head into the unconsolidated substrate. Cores may be shorter than the height of the coral head where the base of the coral head has been damaged by boring organisms. All of the cores are of good quality in the upper 0.6 m, although below that depth damage by boring organisms is common.

Site	Dunk Is	Kumboola Is	Bedarra Is	Coomb Is	Hudson Is	Brook Is
Core code	DUN	KUB	BED	COO	HUD	BRO
Height of coral head (approx.)	2.0 m	1.5 m	1.2 m	2.1 m	1.8 m	5.0 m
Length of core	2.1 m	0.7 m	1.4 m	2.3 m	1.3 m	3.0 m*
Estimated age**	124 y	34 y	***	141 y	88 y	> 100 y
Core quality ****	A	A; 0-.6 m D; .6 -.7 m	B; 0-.7 m C; .7-1.4 m	A	A; 0-.7 m C; .7-1.3 m	A: 0-3.0 m

Table 6.1.1
Summary descriptions of coral cores chosen for analysis.
(* - intersects older bommie; ** - based on counting fluorescent bands, the most practical and reliable estimate of age available from the unprocessed core; *** - hiatus in growth, no age estimate; **** - A = good; B = medium; C = poor; D = very poor.)

The core sections were cemented onto lengths of stainless steel channel using plaster of paris. Slabs 7 mm and 1.7 mm thick were precision cut from each using a milling machine. The coral slabs were then washed in distilled water and dried. Both the coral slabs and the remaining section of the core are stored in a light-proof environment to eliminate the possibility of decay of their fluorescent banding by exposure to light. These slabs were used for the analysis of skeletal fluorescence (Chapter 6.2) and of skeletal geochemistry (Chapter 7).

6.2 SKELETAL FLUORESCENCE:

6.2.1 *Introduction:*

Isdale (1984) showed that massive corals of the genus *Porites* contain bands which fluoresce under long-wave UV light, and were shown to be annual by comparison with skeletal density. The intensity of fluorescence of these annual bands in corals from Pandora Reef is consistent with the strongly seasonal annual discharge peaks from the adjacent Burdekin River, 135 km to the south with a catchment area of 130 000 km^2. The Burdekin River plume flows northward in nearshore waters and does not normally reach mid- or outer-shelf reefs (Wolanski and Jones, 1981). No fluorescent banding has been observed in living corals from the outer GBR, suggesting that the fluorescence may be due to compounds originating on the land.

When viewed under long-wave UV light a coral slab has a faint bluish tinge. In corals from nearshore environments this low intensity fluorescence is apparently displaced by yellow-green bands of high intensity fluorescence. Black and white photographs showing the pattern of fluorescence in *Porites* corals from Rockingham Bay, illuminated with UV light, are presented in Fig. 6.2.1. Note that the fluorescence intensities are consistent with the pattern of sediment plume movement described in Chapter 5.

Fluorescent bands occur at reasonably regular intervals roughly parallel to their adjacent bands and are consistent with formation at, or close to former growth surfaces of the coral, as indicated by both visual inspection and X-radiographs. The yellow-green bands are highly variable in their intensity and width, are often skewed with the tail in the direction of growth, and commonly two or more high-intensity peaks occur within a given annual band.

The strong contrast between the blue background and yellow-green bands is, to a large extent, a result of the human eye response at the wavelengths near the maximum difference in emission intensity (Boto and Isdale, 1985). Emission spectra (Fig. 6.2.2) show that the actual difference is quite small.

Boto and Isdale (1985) showed the source of the yellow-green fluorescence to be terrestrial fulvic acids, apparently differing in both chemistry and structure from marine fulvic compounds. They also demonstrated that the blue fluorescence which is ubiquitous in terrestrial and marine waters occurs throughout nearshore coral skeletons. Boto and Isdale's (1985) experimental evidence for a terrestrial origin of the yellow-green bands is as follows:-

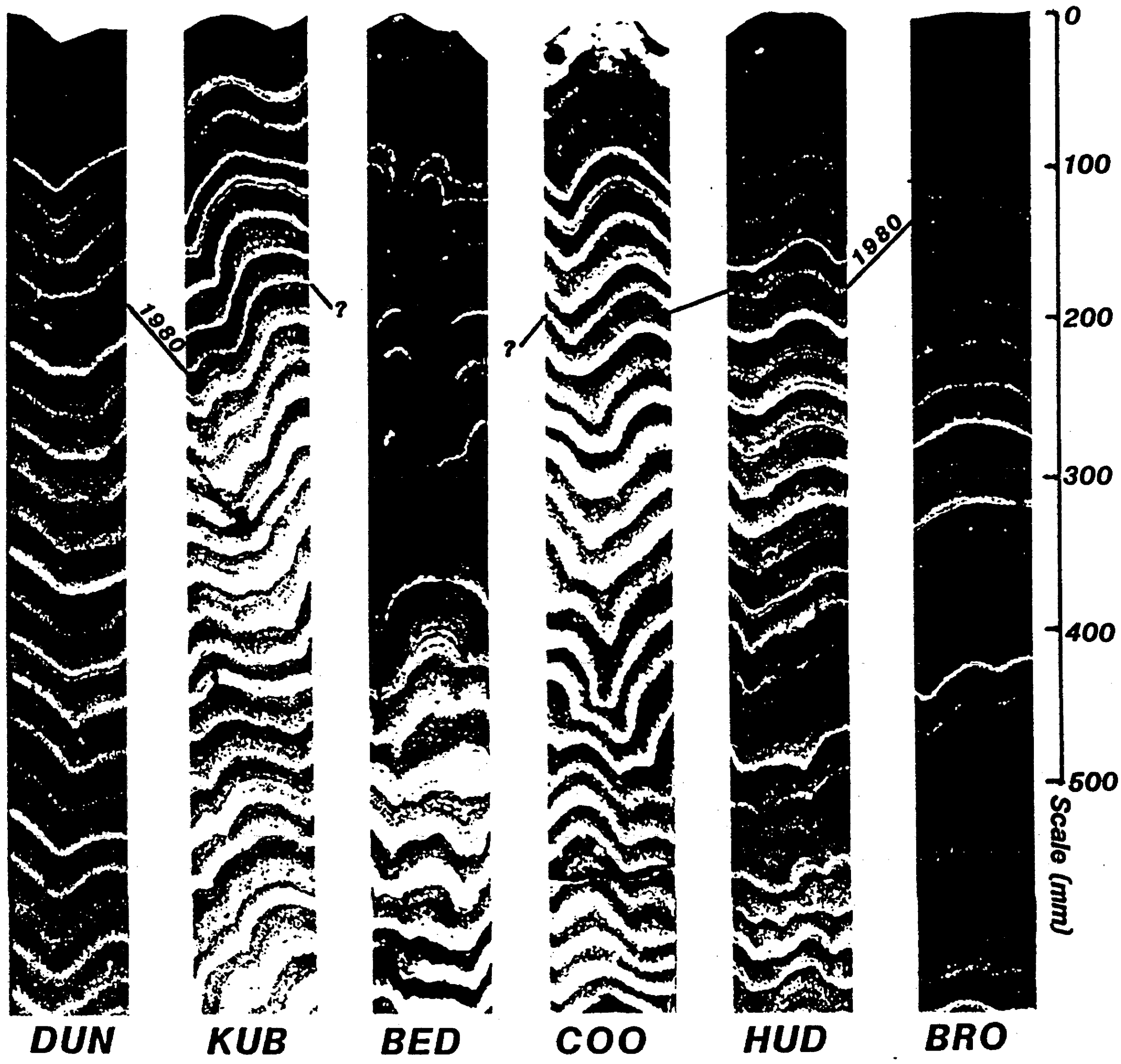


Fig. 6.2.1
The pattern of fluorescence in *Porites* corals from Rockingham Bay under UV illumination.

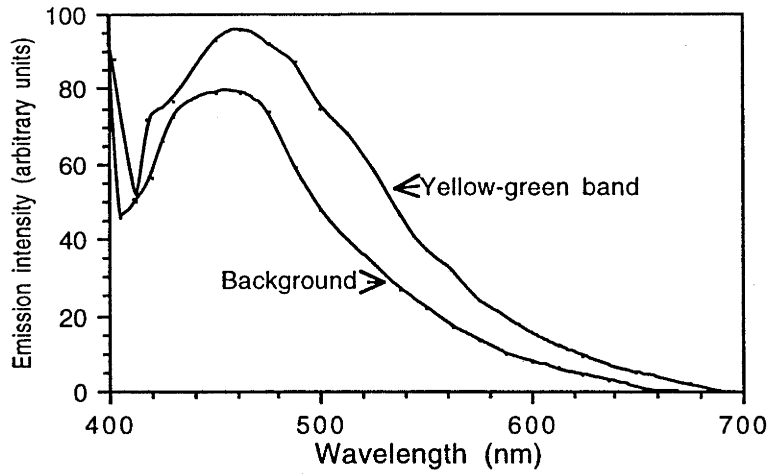


Fig. 6.2.2
Emission spectra of the yellow-green band and background regions of an inshore *Porites* spp. coral skeleton (from Boto and Isdale, 1985).

(i) Extracts of coral skeleton in both dilute HCl and 0.1M NaOH produced solutions with excitation and emission spectra typical of humic compounds.

(ii) Fluorescence intensity was reduced by 30 % and a 25 nm shift in the wavelength of maximum emission occurred when excess Fe^{3+} was added to the acid solutions or the alkaline extracts, consistent with the spectral response of iron - humic compounds.

(iii) When the fast growing branching coral *Acropora formosa* was incubated in seawater containing a fulvic acid soil extract, yellow-green fluorescence was induced in the coral skeleton,

These experimental results are good evidence that the yellow-green fluorescence in massive corals is induced by river-borne terrestrial humic compounds.

Susic *et al.* (1991) summarise the processes by which fluorescent bands are induced in nearshore corals as follows:- Plant matter (leaves, wood, bark, flowers and fruit) contains high concentrations (eg. 1 300 - 5 000 $\mu g.g^{-1}$ dry weight) of humic acids. During decomposition, humic acid concentrations decrease as they are transferred to the soil. Soil humic acid concentrations are highest under dense vegetation (eg. rainforest; 3 - 4.5 $.10^{-3}$ $\mu g.g^{-1}$), about an order of magnitude less under open sclerophyll forest, and less again under grassland, and decline with depth in the soil. Soil humic acid is transferred to streams during rainfall, adsorbed to sediments and in solution. Humic acid concentrations in stream waters are 2 - 10 times that in nearshore sea water, so increased humic acid concentrations occur in the nearshore environment following runoff events, and decline rapidly offshore (Humic acid appears to be conservatively diluted, not precipitated, in seawater (Susic *et al.*, 1991)). As a result, fluorescent bands in nearshore corals (c. <15 km offshore) have humic acid concentrations 1.2 - 2.8 times greater than non-fluorescent band concentrations, 1.01 - 1.1 times greater at 60 - 120 km offshore, and bands are undetectable at 200 km offshore (Susic *et al.*, 1991). Coral skeletal concentrations of humic acids are commonly two orders of magnitude greater than in surrounding seawater (Susic *et al.*, 1991), consistent with the ability of humic acids to complex with calcium (Dempsey and O'Melia, 1983). No change in the distribution of these bands within the coral is apparent over hundreds of years indicating that, at this time scale, the signal is stable.

These findings suggest that good surrogate records of terrestrial runoff which may extend > 500 years (Isdale, 1984), are contained in massive coral skeletons. These records may usefully supplement long term meteorological and hydrological data which are sparse in many tropical areas.

Isdale (1984) examined the relationship, at annual increments, between fluorescence intensity in *Porites* spp. massive corals from Pandora Reef, and stream flow in the Burdekin River. Annual fluorescence was calculated as the sum of four measurements, at equal intervals along the fluorescence trace, between the annual fluorescence minima. These measurements were made after the interpreted average background signal for each year was removed. This measure of skeletal fluorescence is an estimate of the area under the curve, with average background removed, and standardised for the base width of the curve, for annual increments. Burdekin discharge was calculated as the total for the water year. Correlation analysis showed that there was a significant relationship ($r^2 = 0.80$; $n = 62$ years) between the cube of annual fluorescence and the annual Burdekin stream flow (Isdale, 1984). Isdale's figure illustrating this relationship is reproduced in Fig. 6.2.3a. Using a time series of cumulative deviations from the mean, Stewart *et al.* (1989) demonstrated a strong relationship between the Pandora Reef fluorescence record and the Burdekin River rainfall and stream flow records (Fig. 6.2.3b). A direct comparison of this result with the previously reported results is not possible because of the manner of presentation. The site locations chosen mean that the data sets are not independent. Extended to the period prior to historical or instrumental records, their results indicate a long period (1770 - 1870) of below average coral fluorescence and, by extension, low rainfall and stream flow in the Burdekin River catchment. Fluorescence records from nearshore *Solenastrea bournoni* corals in Florida Bay indicated a decline in freshwater inflow to Florida Bay of about 59% attributed to construction of an extensive network of canals diverting stream flow. Fluorescence explained 57% of variance in discharge for the period 1961-1986, and 45% for the period 1940-1960 (Smith *et al.*, 1989). The relatively low explanatory

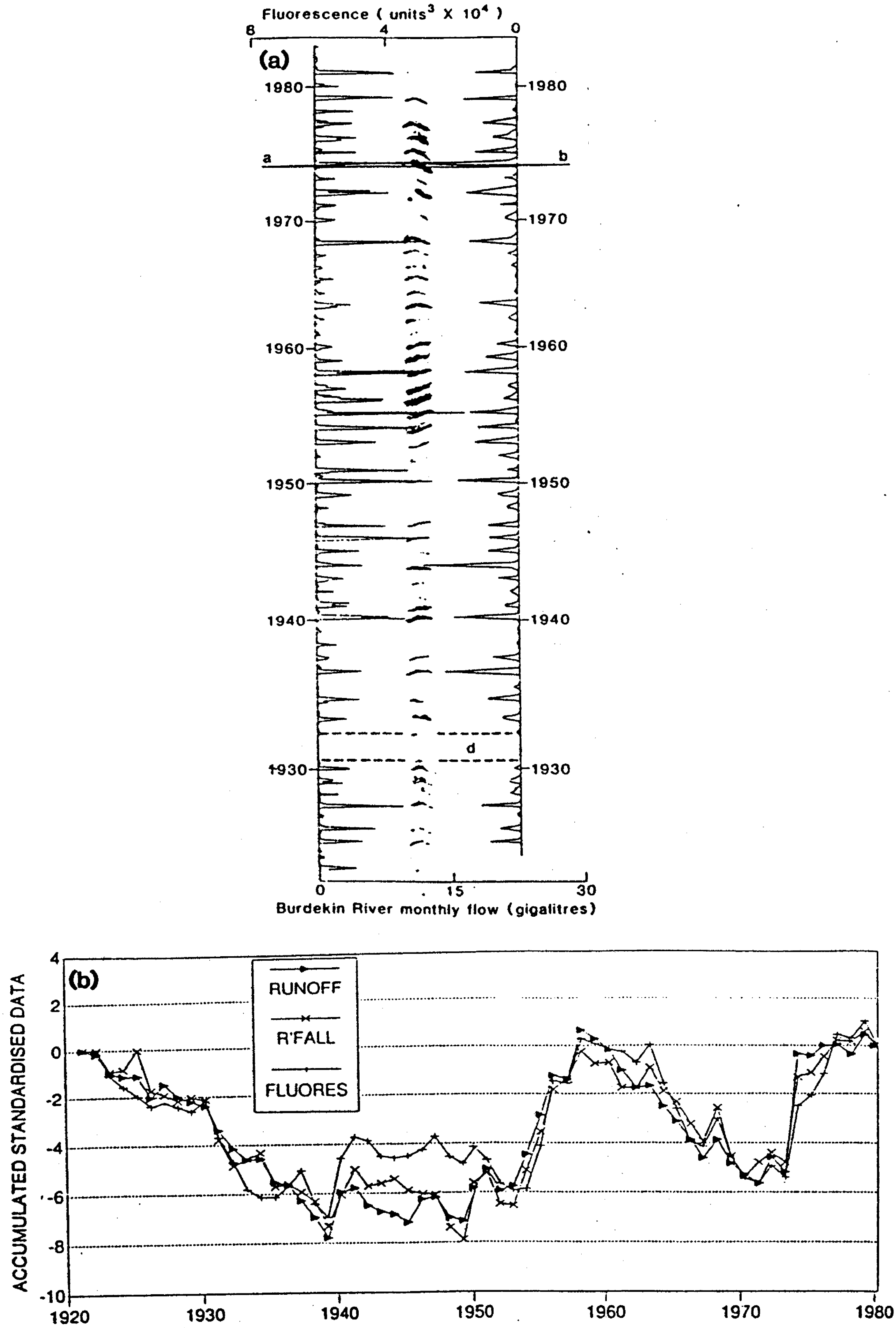


Fig. 6.2.3
(a) The relationship between annual fluorescence and the annual Burdekin stream flow (from Isdale, 1984).
(b) The relationship between time series of cumulative deviations from the mean for the Pandora Reef fluorescence record and the Burdekin River rainfall and stream flow (from Stewart *et al.*,1989).

power in the Florida Bay study may be related to lower stream flow variability than for the Burdekin. Scoffin *et al.* (1989) confirmed the decline of yellow-green fluorescence intensity with distance offshore in *Porites lutea* skeletons from the south coast of New Guinea and the north coast of Java.

Fluorescent bands in massive corals also have application in paleoclimatology. Fossil corals obtained from uplifted late Quaternary coral terraces in the Gulf of Eilat contain seasonal fluorescent bands. Living corals from a low-level, modern terrace in the same sequence do not (Klein *et al.*, 1990). This finding, corroborated by analysis of the humic acid concentrations within the samples, is interpreted as evidence for the northward movement of the monsoon belt over the Sinai during high sea-level, inter-glacial periods, and provides supporting evidence for linkages between monsoonal flow, inter-glacial periods and orbital insolation.

6.2.2 Methods:

Fluorescence intensity along each core section, following the alignment of coral growth, was measured using a custom built fluoromicrodensitometer (Fluorac; described by Isdale (1984), Boto and Isdale (1985) and Isdale *et al.* (in prep.)) at AIMS. The slab is illuminated by UV light (360 nm) transmitted in a 3 mm diameter beam through a Wild-Leitz PLOEM-OPAK fluorescence illuminator. Emitted fluorescence (490 nm) is measured using a Varian AA6 atomic absorbtion spectrophotometer. Although this wavelength is marginally outside the range in which the yellow-green fluorescence maximum occurs (Boto and Isdale, 1985), it minimises the frequency with which the instrument goes off scale in nearshore corals with relatively high fluorescence intensities. Measurements were made at 0.532 mm increments which, on average, are equivalent to about two weeks growth for the sampled corals. Each fluorescence measurement is accompanied by a reference measurement of the lamp output, to standardise the fluorescence record. A detailed description of the method is given by Isdale *et al.* (in prep.). The fluorescence data were then analysed in relation to the available stream flow data. The Fluorac system also incorporates a system for gamma densitometry (Chalker and Barnes, 1990) using a ^{210}Pb source mounted beneath the coral slice. As the coral slice is stepped beneath the UV beam it also passes through a gamma beam from the ^{210}Pb source. A gamma scintillation detector is mounted above the coral slice and connected to an amplifier/pulse height analyser, counter/timer and an interfacing, control and data processing computer. Density of the 7 mm thick slices was also determined using previously described techniques for X-radiography of coral skeletal material (Chalker *et al.*, 1985).

The annual periodicity of the fluorescence peaks was determined by reference to the skeletal density data (as determined by both X-radiography and gamma densitometry). However, the fluorescent bands themselves are probably the more reliable indicator of the annual growth cycle in these nearshore corals, as density may be confounded by "stress bands", and were used to identify the annual series. Fluorescence years were defined from the minimum fluorescence in one year to the minimum fluorescence in the following year. Given that the annual fluorescence peaks are inferred to be a response to seasonal stream flow peaks, the calendrical timing of the fluorescence peaks cannot be determined from the fluorescence data alone as the time of the wet season varies from year to year.

<u>6.2.3 *Hypotheses about the relationship between fluorescence and discharge:*</u>

The relationship between the Rockingham Bay skeletal fluorescence and the Tully River discharge was investigated quantitatively by testing the following specific hypotheses:

(i) **The area under the fluorescence peak is correlated with the total annual discharge,**

(ii) **Area/total discharge relationships are stronger than area/instantaneous discharge relationships,**

(iii) **The peak height of the fluorescence curve is correlated with the short-term discharge maxima,**

(iv) **Peak height/instantaneous discharge relationships are stronger than peak height/total discharge relationships,** and

(v) **Area/total discharge relationships are stronger than peak height/total discharge relationships.**

Linear regression analysis was used to test these hypotheses. The nature of the relationship between fluorescence intensity and stream flow in adjacent rivers is not known, so various measures of the area under the fluorescence curve and fluorescence peak height were tested.

The conceptual model which underlies the stated hypotheses and the choice of the fluorescence and stream flow parameters is summarised in Fig. 6.2.4.

	Qt	Qp	Qi
Peak area (Fa)	√	?	?
Peak height (Fp)	?	?	√

Fig. 6.2.4
Conceptually ideal model of the relationship between stream flow and fluorescence; √ = conceptually ideal relationship, ? = obfuscation of the ideal relationship, Qt = annual stream flow total, Qi = instantaneous maximum stream flow, Qp = some period between Qt and Qi, all Q for water years.

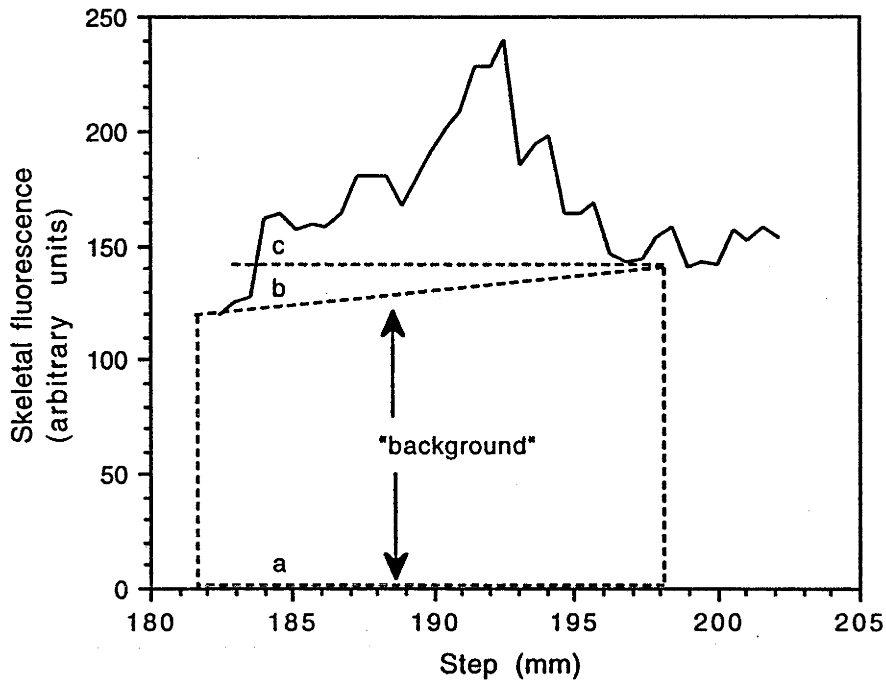
The model identifies conceptually ideal relationships between fluorescence and discharge, and contrasts these with others which imply obfuscation of the relationship by physical processes including persistence, mixing and diffusion of fulvic compounds in seawater and the biological processes of inclusion of fulvic compounds in the coral skeleton. Several purposes are served by investigating the fluorescence - stream flow relationship within this framework, including:

(i) An empirical estimate of the time period over which the coral integrates the stream flow.

(ii) An indication of the degree of obfuscation of the ideal relationship by physical and biological processes, the contribution of which is unknown.

(iii) Identification of the fluorescence parameter which gives the most reliable estimate of Tully River stream flows prior to commencement of stream gauging.

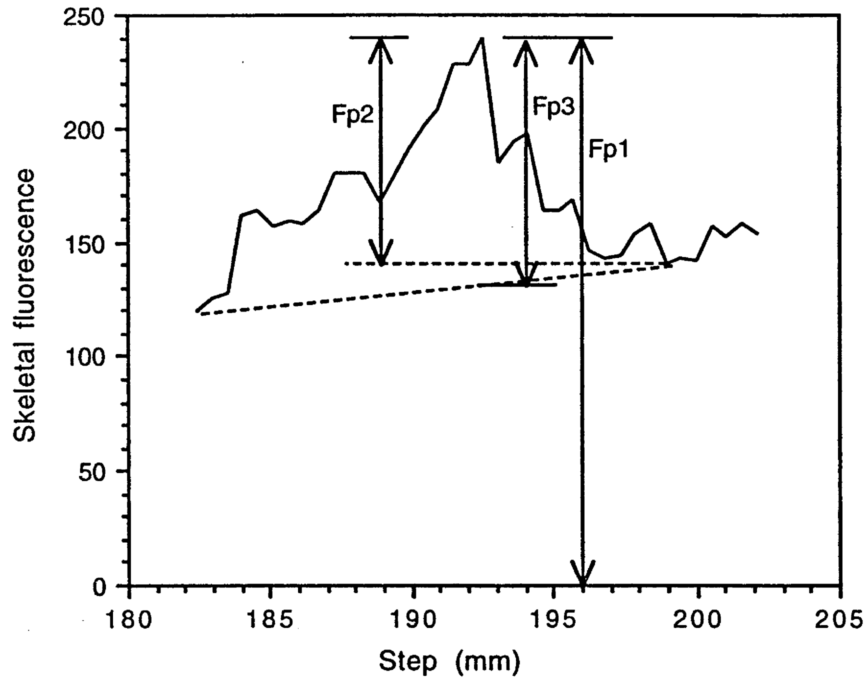
Twelve different measures of area under the fluorescence curve were used. Their derivation is illustrated in Fig. 6.2.5. Both raw fluorescence data and smoothed data were used. Smoothing was done with a nonlinear 'hanning' filter which is robust against long-tailed or spiky (unsupported) noise (Velleman, 1980). The background fluorescence signal (Fig. 6.2.5) was removed for some analyses to test its effect. Both the average background for a given year and the background for the previous dry season were used. Standardisation for the width of the fluorescence curve base was tested to ascertain whether the effect of interannual variation of growth rate on the area under the fluorescence curve could be corrected using the fluorescence data alone. Standardisation was by dividing the area under the fluorescence curve, between annual minima, by the length of core between those minima, that is, the distance between fluorescence minima is always one fluorescence year.



<------- Direction of growth

Fig. 6.2.5
Measures of skeletal fluorescence peak area used to investigate the relationship with discharge. Area above line 'a' denoted Fa1 (smoothed data) and Fa2 (unsmoothed data); Fa3 and Fa4 - as for Fa1 and Fa2 then standardised for variation in annual growth increment; Fa6 (smoothed) and Fa8 (unsmoothed) - area above line 'b'; Fa5 (smoothed) and Fa7 (unsmoothed) - area above line 'c'; Fa9, Fa10, Fa11, Fa12 - as Fa5, Fa6, Fa7, and Fa8 then standardised for variation in annual growth increment.
N.B.:- i. the same arbitrary fluorescence units are used throughout this chapter; ii. Fa10 is similar to the measure used by Isdale (1984) and Stewart *et al.* (1989).

As Isdale (1984) suggested that multiple fluorescent bands within a single growth year were due to multiple flood events, the relationship of peak fluorescence to discharge characteristics was also investigated. Five descriptors of the fluorescence peak height (Fig. 6.2.6) were tested. Peak height analysis followed the same pattern as that described for area under the curve, although in these cases no standardisation was necessary.



<------- Direction of growth

Fig. 6.2.6
Measures of skeletal fluorescence peak height used to investigate the relationship with discharge. Fp1, Fp2 and Fp3 are calculated from the unsmoothed fluorescence curve; Fp4 and Fp5 are calculated as for Fp3 and Fp2, respectively, but using the smoothed fluorescence curve.

Stream flow data from the Tully River at Euramo (Stn. 113006A) for the years 1973 to 1986, inclusive, were used in the analyses. Therefore, for all comparisons reported, n = 14. Stream flow variables included in the regression analyses are defined as follows:-

Q_i	The maximum instantaneous stream flow for the water year.
Q_1	The maximum one day stream flow for the water year.
Q_{14}	The maximum stream flow for any continuous 14 day period in the water year.
Q_{30}	The maximum stream flow for any continuous 30 day period in the water year.
Q_{60}	The maximum stream flow for any continuous 60 day period in the water year.
Q_{90}	The maximum stream flow for any continuous 90 day period in the water year.
Q_t	The total stream flow for the water year.

The water year (October to the following September) was used in all analyses to correspond with rainfall seasonality.

Linear regression was used for all of the analyses carried out. Preliminary interrogation of the data produced no evidence to suggest that any form of non-linear relationship was appropriate.

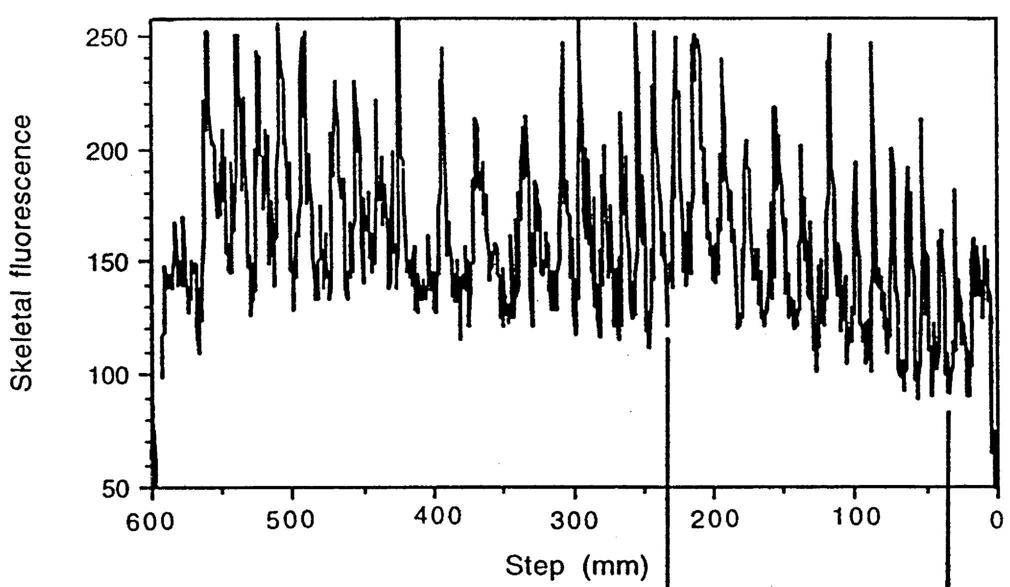
6.2.3 Results and discussion:

6.2.3.1 General characteristics of the fluorescence time series:

An example of a fluorescence trace for a Rockingham Bay coral core is given in Fig. 6.2.7. The example used is that of the KUB core. The figure shows clearly the marked difference in fluorescence between the relatively narrow fluorescent bands and the areas between the bands. It also illustrates the variability of the background signal on which the annual signal is imposed, and the inter-annual variation in the base of the annual fluorescence peak. These factors are taken into account in the following analysis. Although the figure indicates that several peaks are at the maximum fluorescence value (255), no peak in this analysis is actually off-scale.

Another feature of Fig. 6.2.7 is the marked variation in apparent growth rate during different periods of the colony's life, illustrating quantitatively what is also evident for the core sections shown in Fig. 6.2.1. Assuming that the fluorescence peaks represent a complete annual series with every year represented, apparent growth rates have been estimated for different sections of the KUB core (Table 6.2.1). Apparent growth varies by as much as a factor of 2.5 between different parts of the core. Although the cause of this variation in apparent growth rate is unknown, inspection of the relevant core section suggests that it is due to both actual inter-annual differences in growth rate and to differences in the orientations of the drilling axis and the coral growth axis. Differences in growth rate may affect the incorporation of fulvic acids into the coral skeleton and, therefore, the fluorescence-discharge relationship.

Fig. 6.2.8 shows the time series relationship between fluorescence in the KUB core, using smoothed data with the background fluorescence removed, and Tully River discharge for the fourteen years 1973 - 1986. Qualitatively, there is a reasonable correspondence between the two records, although there are obvious inconsistencies, mostly related to peak magnitude and years with multiple flood peaks.



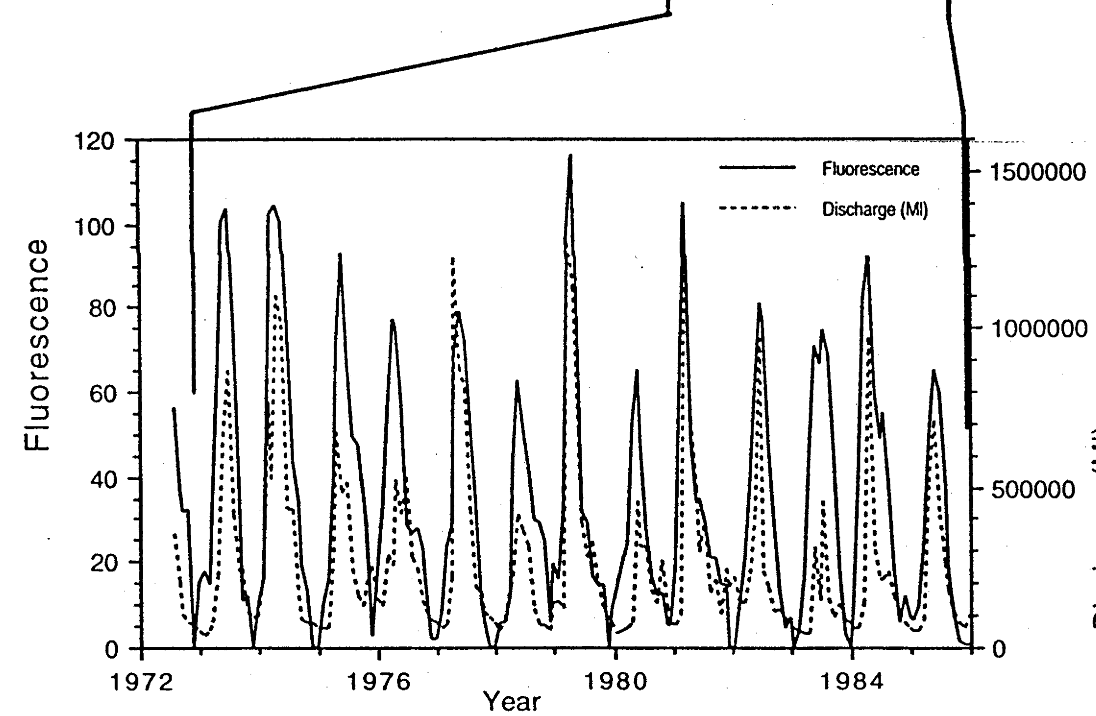


Fig. 6.2.7 (top)
Time series of skeletal fluorescence (raw data) for the KUB coral core from Rockingham Bay.

Fig. 6.2.8 (bottom)
Time series of Tully River monthly discharge and smoothed coral skeletal fluorescence (KUB core) for 1973 to 1986. Fluorescence data are normalised by manual alignment of maxima and minima with the equivalent positions in the discharge trace.

Core depth (mm)		Apparent growth rate ($mm.yr^{-1}$)	
38 - 313		14.6	
	38 - 127		13.0
	128 - 232		17.5
	233 - 313		13.5
314 - 410		32.0	
411 - 564		17.1	

Table 6.2.1
Variation in apparent growth rate for different periods in the KUB core; Growth rates determined from the fluorescence peak intervals in Fig. 6.2.7

6.2.3.2 Simple relationships between the area under the fluorescence curve and discharge:

The relationship between the area under the fluorescence curve (Fa) and river discharge improves as the discharge period used is increased from the instantaneous maximum up to the annual total (Fig. 6.2.9). The fluorescence parameter Fa8 (unsmoothed, unstandardised, average background removed) is used to illustrate the pattern, although all fluorescence parameters exhibit similar patterns.

The value of R^2 is in the range 0.003 to 0.044 (for the five cores analysed) when Fa8 is regressed against the maximum instantaneous discharge (Qi) and rises to 0.110 to 0.621 for total annual discharge (Qt) (Fig. 6.2.9). Although the latter result is significant for coral cores from only four of the five sites ($p<0.05$; $n=14$) the general pattern is consistent with the hypothesis that the area under the fluorescence peak is correlated with the annual discharge (Hypothesis (i)). The figure also shows that the average Fa8 value for the five cores in the analysis ($\bar{x}$ (Fa8)) follows the same pattern as for the individual cores but results in no improvement to the coefficient of correlation. Only 50% of total discharge variance is explained by the five site mean of Fa8. The regression equation which fits these data is:

$$Q_t = 2\,888\,\bar{x}\,(Fa8) + 1.28 \times 10^6 \quad (n = 14; R^2 = 0.53; p \leq 0.01) \qquad \text{[Eqn. 6.2.1]}$$

It should be noted that, although total annual fluorescence is best correlated with the total annual stream flow, it is unclear how this can be recorded as low discharges may carry little or no fulvic acid and would be unlikely to reach the coral growth site.

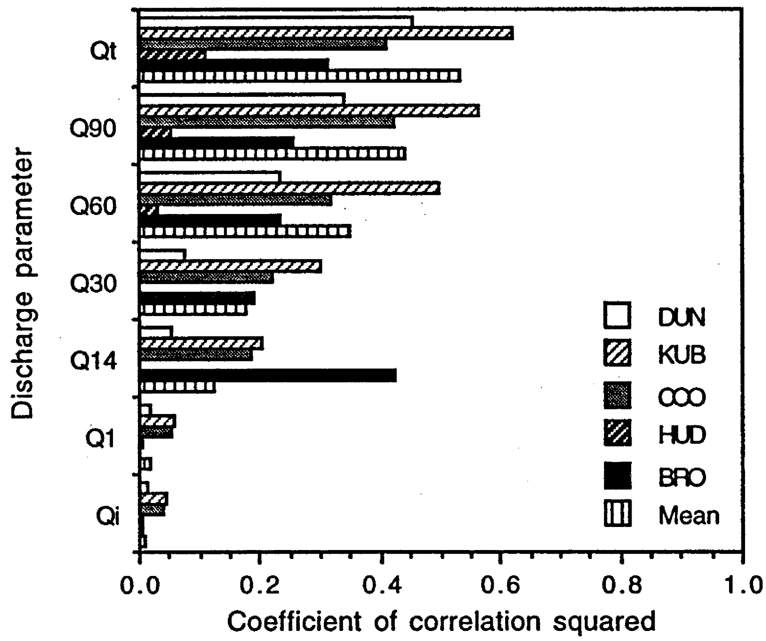


Fig. 6.2.9
Relationship of Fa8 to discharge characteristics for each of the five cores, and their mean.

Fig. 6.2.10 shows that, on average, the fluorescence area parameters which are best correlated with the annual discharge total are Fa7 and Fa8, as defined in Fig. 6.2.5. These results also indicate the importance of removal of the background signal, as in Fa5 - Fa8, by comparison with the relatively poor correlations using fluorescence parameters without the background signal removed (Fa1 - Fa4). Standardised fluorescence parameters (Fa3, 4, 9, 10, 11, 12) are generally not as strongly correlated with Q_t, by comparison with the same parameter without standardisation (i.e. Fa1, 2, 5, 6, 7, 8, respectively). This suggests that the fluorescence signal in the coral skeleton is little affected by skeletal growth rates.

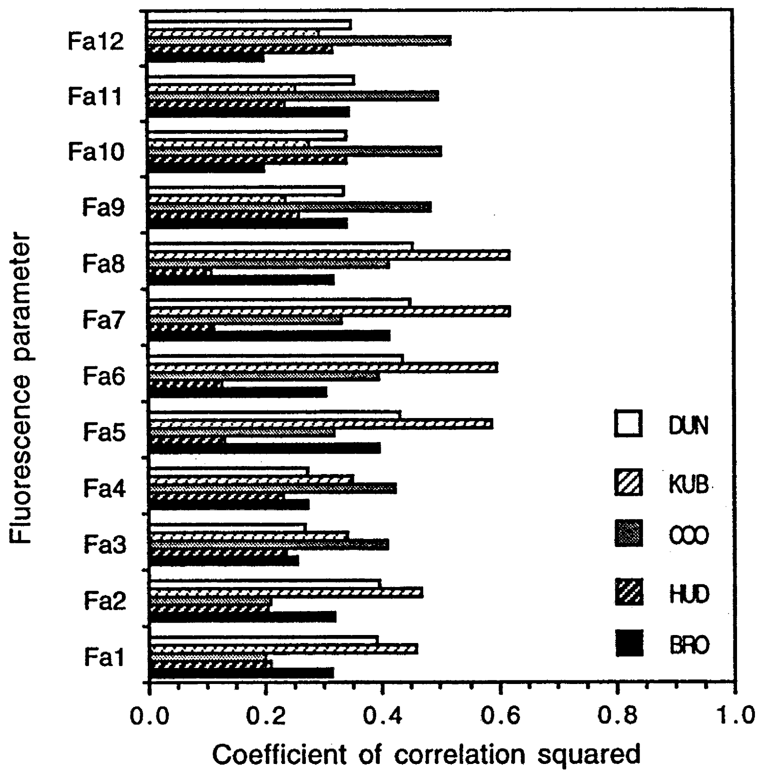


Fig. 6.2.10
Relationship of area under the fluorescence curve (Fa1-Fa12) to total annual discharge in the Tully River.

This analysis indicates that:

(i) Hypothesis (i) is supported and annual total stream flows are correlated with the area under the discharge curve.

(ii) The best correlate of total discharge is a fluorescence parameter which is unsmoothed and unstandardised with the average background removed.

(iii) The correlation between fluorescence peak area and total discharge is stronger than that between peak area and instantaneous discharge, supporting hypothesis (ii).

(iv) The mean fluorescence of the five cores is generally better correlated with total discharge than is fluorescence in a single core, the exception being the KUB core (Fig. 6.2.9).

<u>6.2.3.3 *Simple relationships between peak height of the fluorescence curve and discharge:*</u>

To test hypothesis (iii), that the peak height of the fluorescence curve should correlate with the discharge maxima, five fluorescence peak height parameters, as defined in Fig. 6.2.6, were first tested by regression against the instantaneous maximum discharge to identify the one which was best correlated with discharge. A full analysis of all Fp measures vs all Q measures showed that the fluorescence peak parameters for a given discharge period are more consistent between cores than is the case for the area parameters. The Fp measure best correlated with Q_i is Fp5, although there is only a small difference between the different measures.

Fp5 was then tested against each of the discharge parameters, as the time interval which the fluorescence peak height represents is not known. Surprisingly, the discharge parameter which is best correlated with Fp5 is the annual total (Fig. 6.2.11), not a short period discharge as hypothesised. The relationship with the annual total discharge is significant in all cases ($p < 0.05$; n=14). The same general pattern of improving fit with increased discharge period as was observed in the peak area data is observed, with R^2 increasing from the range 0.009 to 0.084 for the relationship of Fp5 with Q_i to the range 0.468 to 0.667 for Fp5 v Q_t. The fluorescence peak height alone explains between 46% and 66% of the variance in Q_t. The correlation between the mean Fp5 ($\bar{x}$ (Fp5)) for the five cores and Q_t (R^2=0.734) is better than for the individual cores. No combination of Fp5 averages yields a better relationship with Qt than the mean of all five cores. This suggests that no particular spatial grouping of core sites yields a better record of stream flow than does the total data set. The regression equation which fits these data is:

$$Q_t = 39\,244\ \bar{x}\,(\text{Fp5}) + 0.85 \times 10^6 \quad (n = 14; R^2 = 0.73; p \leq 0.001) \qquad \text{[Eqn. 6.2.2]}$$

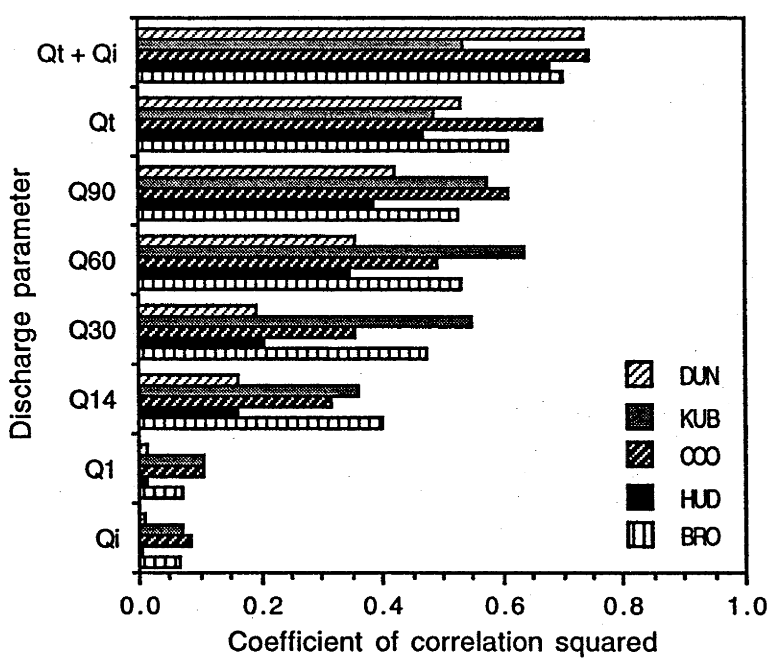


Fig. 6.2.11
Relationship of Fp5 to discharge characteristics for each of the five cores, and their mean.

Given that the fluorescence peak heights are best correlated with the total discharge, rather than the instantaneous or one day maxima, the five fluorescence peak height parameters were tested against the discharge total. Fp5, smoothed data with the previous background removed, is again the best correlated with total discharge (Fig. 6.2.12)

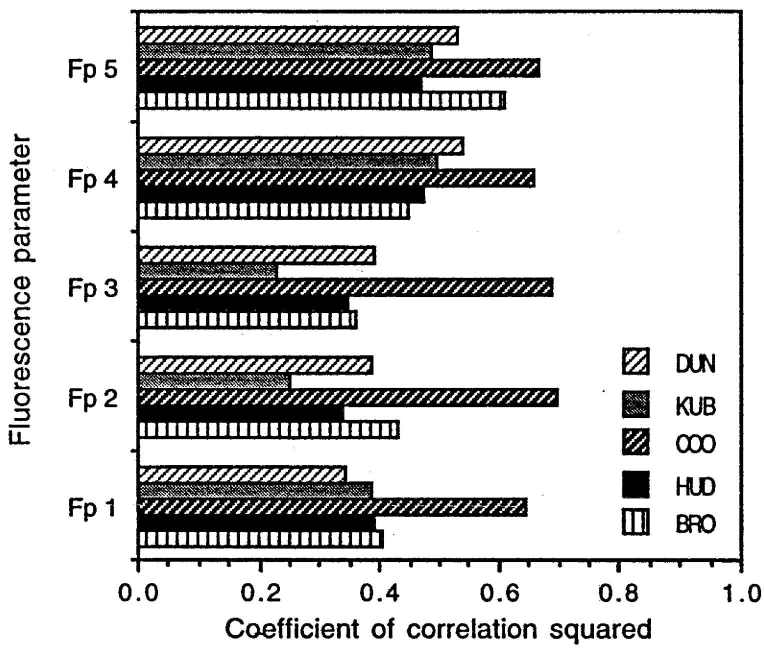


Fig. 6.2.12
Relationship of fluorescence peak height (Fp1-Fp5) to total annual discharge (Q_t).

The analysis shows that:

(i) The fluorescence parameter best correlated with discharge is derived from smoothed data with the previous background removed.

(ii) The mean of the fluorescence peak heights (Eqn. 6.2.2) is better correlated with total discharge than is the data from any individual core.

(iii) Hypothesis (iii), that the peak height of the fluorescence curve should correlate with the short-term discharge maxima, is not supported.

(iv) Hypothesis (iv), that peak height/instantaneous discharge relationships are stronger than peak height/total discharge relationships, is rejected.

(v) Hypothesis (v), that peak area/total discharge relationships are stronger than peak height/total discharge relationships is rejected.

The relationship between skeletal fluorescence and stream flow may be a simple one, in which corals incorporate fulvic acids into their skeleton at concentrations directly proportional to the discharge from adjacent streams. This is the basis of the ideal conceptual model described in Fig. 6.2.4. For this model to apply, all five of the stated hypotheses must be accepted. Hypotheses (i) and (ii) were accepted, but hypotheses (iii), (iv) and (v) were rejected. Consequently, the process relationship between Tully River stream flow and Rockingham Bay coral skeletal fluorescence is most uncertain.

6.2.3.4 Two-parameter model of the relationship between fluorescence and discharge:

Fig. 6.2.13 shows that inclusion of the instantaneous (Q_i) or the one day (Q_1) discharge maxima significantly improves the relationship between the annual total and Fp5. In all cases the Q_t coefficient is positive, while that for Q_i or Q_1 is negative and significant. The pattern of Fa8 in relation to these discharge parameters is similar to that shown, although the fit is not as good as for Fp5. The correlation of the mean peak height for the five cores, in relation to multiple discharge parameters, is substantially better than that for the individual cores. The mean R^2 for the five cores (Fp5 v. $Q_t + Q_1$) is 0.686 (range = 0.520 - 0.758) while that for the five core mean ($\bar{x}$ Fp5 v. $Q_t + Q_1$) is 0.904. The regression equation which fits these data is:

$$\bar{x}(\mathrm{Fp5}) = 2.66 \times 10^{-5} .Q_t - 9.88 \times 10^{-4} .Q_1 + 44.04$$

$(n = 14; R^2 = 0.904; p \leq 0.001)$ [Eqn. 6.2.3]

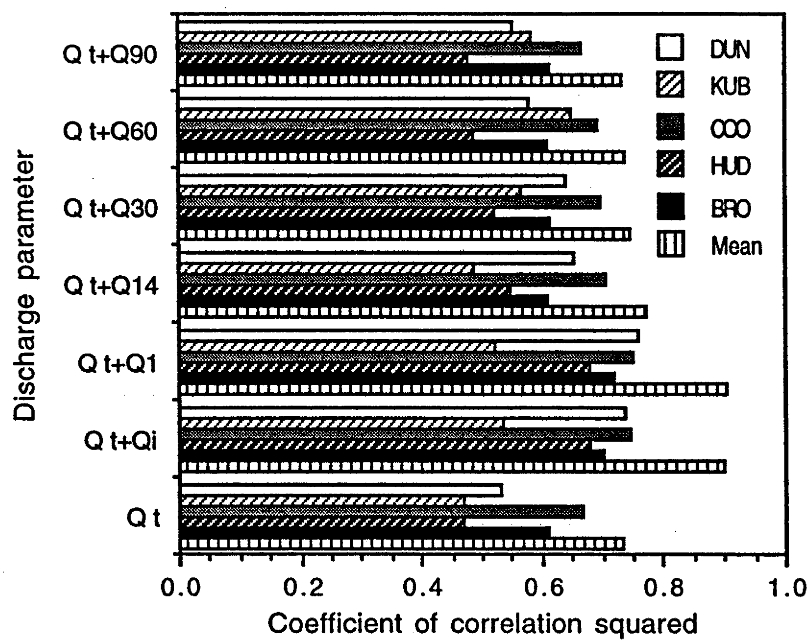


Fig. 6.2.13
Results of multiple regression of Fp5 against Q_t plus short period discharges for each of the five cores, and their mean.

6.2.3.5 Sources of the unexplained variance:

Coral growth rate: Within-coral-colony variation in growth rate plays a role in the pattern of fluorescent band formation, and may influence the relationship between fluorescence and discharge. If fluorescence peak height and Qi were correlated (hypothesis iii), then the peak height would be expected to be unaffected by growth rate. However, hypothesis (iii) was not supported by the data. Peak height is correlated with Qt (Fig. 6.2.11) suggesting that the peak height is integrating the annual total fulvic acid discharge. Consequently, the peak height may be inversely proportional to growth rate.

Coral slabs from small colonies, sectioned through the centre, show the complete pattern of growth and of fluorescent band structure. Slabs from a number of small colonies show that the same fluorescent band may appear as a double band in the part of the colony experiencing rapid vertical growth, as a single narrow band in the part of the colony experiencing very slow lateral growth, and as a broad single band in the intervening area. An example of this pattern, from one band in a small coral head from Bedarra Island, is as follows:- vertical growth of c. 13 $mm.a^{-1}$ - a double band separated by 1.5 mm; intermediate growth rate of c. 6.5 $mm.a^{-1}$ - a single fluorescent band 2 mm wide; and slow lateral growth of c. 4 $mm.a^{-1}$ - a single band about 1 mm wide. Similar variation in fluorescent band width, although not of the same degree, can also be seen within bands in a slice only 80 mm wide. On the other hand, P. Isdale (pers. comm.) reports that parallel traces within an 80 mm width give reproducible records.

It seems likely that interpretations of the structure of river discharge within a given time period, based on fluorescent band structure, will be affected by the growth rate of the coral. Interpretations of total flow, based on fluorescent peak height, will be less affected by the coral growth rate.

River plume movement: Lower or more variable correlation coefficients for the individual cores than for the mean of the five cores may be due to movement of the Tully River plume. No attempt is made to weight the data as there is insufficient knowledge of circulation within Rockingham Bay. The observation that between 46% and 66% of the variance in annual total discharge is explained by fluorescence records from individual sites, and that this improves to 73 % for the mean of the five sites, suggests that plume movement is responsible for some of the unexplained variance.

Resuspension of humic compounds: The effect of windiness was tested. The number of days with strong winds (> 40 $km.h^{-1}$) at Cardwell (Australian Bureau of Meteorology data) was regressed against the residuals of Eqn. 6.2.3. There was no relationship between strong wind occurrence and the residuals. Although Scoffin *et al.* (1989) suggested that resuspension of humic compounds in bottom sediments would influence the skeletal yellow-green fluorescence, this seems unlikely as these compounds decay to blue fluorescing compounds in the marine environment over a period of a few weeks (Susic, 1990; pers. comm.).

Variation in tidal flushing: Although tidal periodicities of greater than one year occur, the variation in tidal range between years is not likely to be sufficient to result in a significant inter-annual variation in tidal flushing in the GBR lagoon (G. Lennon, 1989, pers. comm.) so this is unlikely to be a factor in the relationship between stream flow and fluorescence.

Humic concentrations in river waters: The potential importance of variation in humic concentrations is indicated by the 90% of variance in peak height ($\bar{x}$ of five sites) explained by its relationship with Q_t and Q_1 (Eqn. 6.2.3), compared with only 73 % when Q_1 is not included. The negative sign on the Q_1 term in Eqn. 6.2.3 suggests a dilution of the fulvic acid concentration of humic materials as the proportion of overland flow increases. Negative relationships of solute concentrations to fluvial discharge are widely observed (Richards, 1982; 90-91) and occur for most solutes in the Tully River (Ch. 3). However, the results of Susic and Isdale (1989) indicate that this may not be the case with humic acids, which may have greater concentrations at increased stream flows.

Variation in the source of river waters: Variations in the relative contribution of smaller streams adjacent to the Tully (particularly the Murray) and the likelihood of some input from larger rivers to the south, for example, the Herbert and the Burdekin, are likely to induce some errors in the relationship between skeletal fluorescence in the Rockingham Bay corals and the Tully River discharge. The observation of a northward moving front of relatively high turbidity water, between Hudson and Coomb Islands and attributed to the Herbert River, during the March, 1990 floods (see Chapter 5) is evidence of the latter possibility. It is likely that the Tully River plume exhibits greater variation in direction of movement than the much larger Burdekin plume, and this is reflected in the observed sensitivity of fluorescence records in Rockingham Bay to plume movement.

Variation in sediment concentrations: Soil humic acid is transported both in solution and adsorbed to sediments. As a result, it is likely that the quantity of humic acid reaching reef sites, and incorporated into coral skeletons, is influenced by the suspended sediment concentrations. It is also possible that the humic acid concentration in the coral skeleton, evident as skeletal fluorescence, is a proxy record of fluvial sediment discharge rather than of fluvial water discharge. The rapid decay of the yellow-green fluorescing compounds to blue fluorescing compounds in the marine environment means that any such record would be subject to little interference from bottom sediment resuspension.

A simple preliminary test of this possibility is an examination of the relationship between skeletal fluorescence and the sediment yield time series calculated in Chapter 4 (Figs. 4.3.1 and 4.3.2), and a comparison of these relationships with that for skeletal fluorescence and stream flow for the same time period. Correlation analysis shows that the relationship between skeletal fluorescence and stream flow is stronger than that between skeletal fluorescence and either the sediment yield ($SY_{(EI)}$) or the product of the land use and management index ($SY_{(LM)}$) and stream flow. This applies for each of the five cores analysed and for the mean fluorescence of those cores. There is only one exception in 24 analyses. These results suggest that skeletal fluorescence is a poor recorder of sediment yield.

An alternative hypothesis is that high sediment concentrations at a given stream flow result in lower fluorescence than low sediment concentrations at the same stream flow because humic compounds are adsorbed onto soil particles. Nearshore sediment deposition would remove these humic compounds, reducing the quantity available for incorporation into the corals. A preliminary test of this hypothesis is a comparison of the relationship between skeletal fluorescence and stream flow with the relationship between skeletal fluorescence and the product of Qt and the reciprocal of the sediment yield index shown in Fig. 4.3.1 ($Fp5 = f((1/SYI_{(LM)}) .Qt)$. In all cases except one, adjustment of the stream flow to account for the likely suspended sediment concentration yields an improvement in the relationship with fluorescence (Fig. 6.2.14), suggesting that variations in suspended sediment concentrations may affect skeletal fluorescence in the manner hypothesised. The regression equation which best describes this relationship is:

$$\bar{x}(Fp5) = 1.209 \times 10^{-3} (1/SY_{(LM)}).Qt + 4.238$$
$(n = 14; R^2 = 0.819; p \leq 0.001)$ [Eqn. 6.2.4]

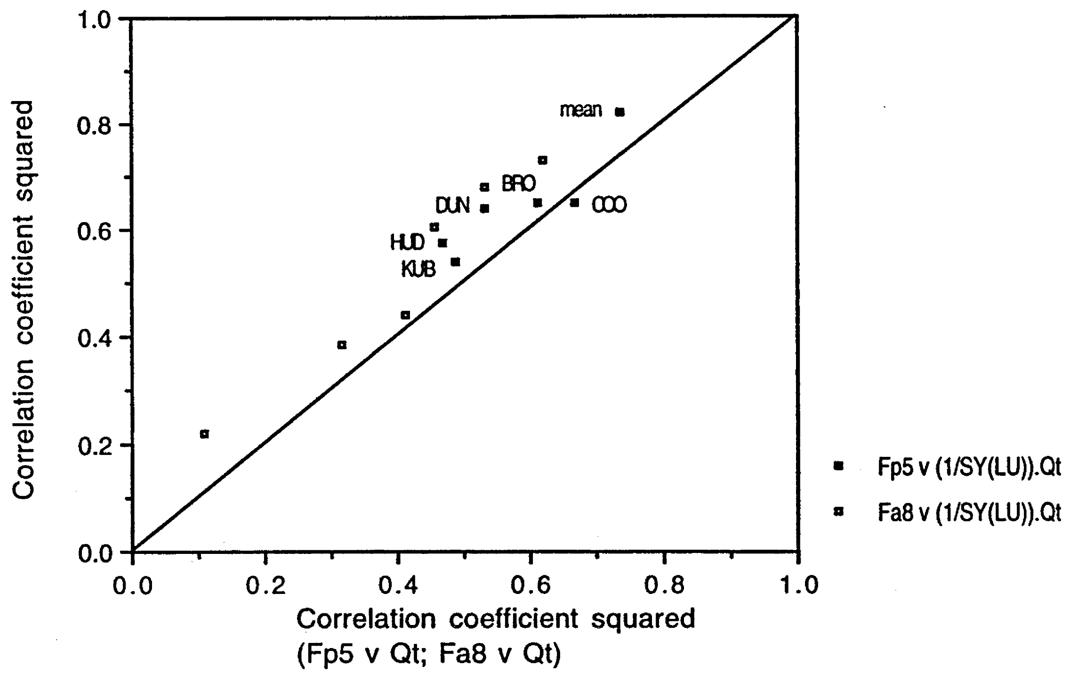


Fig. 6.2.14
Comparison of the variance explained by the relationship between skeletal fluorescence and stream flow and skeletal fluorescence and the product of the inverse of the land use and management index and stream flow.

<u>*Multiple runoff events:*</u> Co-occurrence of multiple runoff events and multiple fluorescent bands in certain years is illustrated in Fig. 6.2.8 for the KUB fluorescence record and monthly discharge data. Two distinct runoff events occurred in four of the years (1974, 1975, 1976, 1983). Of these, two appear in the fluorescence record (1975, 1983). Similarly, Scoffin *et. al.* (1989) note the distinct double fluorescent band in *Porites lutea* growing in southern Papua New Guinea correlated with the bi-modally distributed monthly rainfall of 1981-2. There are three years in which there is a distinct shoulder on the falling limb of the Tully River hydrograph (1979, 1981, 1984), all of which have some expression in the fluorescence record.

<u>*Coral site location:*</u> The absence of a fluorescence response in years when there was a marked increase in stream flow during the dry season (1976, 1980, 1981) indicates that there is a discharge threshold below which the volume of river water is not sufficient to yield a fluorescence signal. It is also notable that the KUB core is from the site closest to the river mouth and has Fp_5 best correlated with Q_{60} rather than Q_t as in the case of all the other cores. This suggests that certain combinations of coral colonies and growth locations may be much more sensitive recorders of terrestrial inputs than others, and following from this, that site selection may be a crucial factor in

getting the maximum resolution from the coral fluorescence. Coral colonies close to the river mouth are more susceptible to hiatuses in growth (as in the BED core), to boring by algae, sponges and worms obscuring banding, and to reduction of wet season/dry season contrast in banding patterns (Scoffin *et al.*, 1989). On the other hand, those colonies beyond the optimum distance will not record some events and are more likely to be affected by runoff from other streams.

6.2.3.6 The role of discharge variability:

Factors other than discharge affect coral fluorescence, as outlined in the preceding paragraphs. Hence, as the inter-annual variability of stream flow decreases these errors will contribute a greater proportion of the inter-annual fluorescence variability. Inter-annual variability in Tully River stream flow is low (c.v. Qt = 33 %) compared to the Burdekin (c.v. Qt = 120 %). This provides a partial explanation as to why the relationship between single core coral fluorescence and stream flow for the Tully River is weaker than that reported by Isdale (1984) for the Burdekin. It is also important to note that the streamflow record itself is not perfect, and some of the errors in the relationship between fluorescence and streamflow may be due to shortcomings in the instrumental record.

6.3 Summary:

Fluorescence intensity in massive corals provides a good measure of fluvial discharge from the Tully catchment. Results of this analysis show a lower correlation between UV fluorescence and discharge than demonstrated for the Burdekin River-Pandora Reef relationship by Isdale (1984). This is attributed to both the lower inter-annual variability of the Tully River discharge and the likely greater variability in the direction of movement of the relatively small Tully River plume. These results from Rockingham Bay corals are comparable with those of Smith *et al.* (1989) in Florida Bay.

Best results for the Tully River are obtained by averaging fluorescence data from all five sites in Rockingham Bay, thereby taking some account of variation in river plume movement. The results also suggest that variations in sediment concentrations in relation to discharge may influence transport of humic compounds to reefal areas.

In general, best results will be obtained by using multiple cores from carefully selected sites. This is likely to be more important in small catchments such as the Tully than in very large catchments (eg. the

Burdekin) because of the more restricted distribution of small catchment river plumes. The higher the seasonality, and the higher the inter-annual variability, the better the coral fluorescence record will measure stream flow.

For the purposes of this research, no contribution to the analysis is made by reconstructing Tully River stream flows from the fluorescence record because a stronger relationship of better temporal resolution can be obtained from the simple monthly runoff model or from the records of adjacent streams with longer periods of gauging (Chapter 3.4.4), and because of the nature of the sediment inclusion record, discussed in Chapter 7.

The coral fluorescence record, while providing a good record of hydrological conditions for sediment yield analyses on annual or decadal time scales, may not have the temporal resolution necessary for high resolution sediment yield studies such as that attempted in this research. The fluorescence record shows that fluvial inputs are recorded and that there is a strong annual signal. The brightest bands probably represent the largest plumes reaching the islands. These plumes probably also represent the highest concentrations of terrigenous sediments at the islands. Chapter 7 reports the results of coral core analysis to determine the concentrations of those sediments and their variation through time.

CHAPTER SEVEN

THE SEDIMENT INCLUSION RECORD IN ROCKINGHAM BAY CORALS

CONTENTS

7.0	GENERAL INTRODUCTION
7.1	SUSPENDED SEDIMENT TIME SERIES
7.2	NUTRIENT TIME SERIES
7.3	SUMMARY

7.0 GENERAL INTRODUCTION:

The ability of coral skeletons to record environmental change, such as lead pollution, phosphorus pollution, and heavy metal concentrations, through variation in their skeletal geochemistry was outlined in the previous chapter. In this chapter the extraction of a terrigenous sediment yield record from the skeletal geochemistry of massive corals from Rockingham Bay is discussed. A review of the interactions which occur between sediments and corals, preliminary analyses to determine whether terrigenous sediments are present in the Rockingham Bay corals, the analytical methods used to obtain a sediment inclusion time series from the coral samples, and the results of these analyses are presented. The same analytical methods were used to investigate a nutrient time series, described in 7.2.

7.1 SUSPENDED SEDIMENT TIME SERIES

7.1.1 Introduction

In principle, a continuous record of variation in seawater suspended sediment concentrations should be available from the skeletons of annually-banded massive corals as a result of inclusion of suspended sediments during calcification. Sources of these sediments are primary terrigenous inputs, transported in river plumes, and secondary, mixed (terrigenous and marine) sediments from bottom sediment resuspension. In this study, a record of primary terrigenous inputs is sought. Given that there is evidence of such a skeletal record, its characteristics and efficacy will be influenced by modes of inclusion of trace constituents, efficiency of sediment exclusion by the coral polyp, and sampling and analytical techniques, each of which is briefly reviewed below.

<u>*Evidence of a skeletal record of terrigenous sediments:*</u> Coral skeletons sometimes contain fine sediment which may cause visible discolouration in bands or patches. Corals also contain dark bands which are not caused by included sediment. These bands can often be seen more clearly by back-lighting, particularly with ultra-violet light. Risk *et al.* (1987) demonstrated that dark grey bands in specimens of *Porites spp.* from Lizard Island, GBR were due to cycles of boring by endolithic algae which, when alive, form the green bands which occur below the growth surface of hermatypic corals (Kanwisher and Wainwright, 1967; Risk and Muller, 1983; Highsmith, 1981). Similarly, Bak and Laane (1987) showed that annual black bands in *Porites* specimens from Indonesia were due to fungal infestations. These types of discolouration make it difficult to identify and quantify included sediment simply by optical scanning.

Dissolution of coral skeleton often leaves a residue of apparently terrigenous detritus. For example, Goreau (1977a), analysing specimens of *M. annularis*, reports "... a reddish residue, similar in colour to the iron-rich bauxites and terra rossa soils ... inland of the sample site ..." at Discovery Bay, Jamaica. As early as 1974 Barnard *et al.* reported a mineralogical study of hermatypic corals which indicated that these corals might contain a continuous record of non-carbonate suspended sediments in the waters in which the coral grew. Their analysis, on three species of massive coral from east coast USA, the Gulf of Panama and the Belize barrier reef, showed that the mineral suite of the non-carbonate detritus was not species specific, and that changes in the mineral assemblage coincided with an increase in the quantity of detritus and clearing of adjacent land. Barnard *et al.* (1974) also suggested that most, if not all Si, Al and Fe, as well as some alkali and alkaline earth elements, found in hermatypic corals are derived from detrital alumino-silicates and other such detritus, a conclusion corroborating the results of Livingstone and Thompson (1971). Livingstone and Thompson also observed that high concentrations of Cr found in certain corals were probably due to incorporation of detritus from Cr-rich ultrabasic outcrops in the area. Macintyre and Smith (1974) suggested that the marked variation in composition of the non-carbonate detrital fraction could be regarded as a record of natural or anthropogenic variation in suspended sediment composition.

Goreau (1977a, b) examined the trace element distribution in samples of *M. annularis* and found no relationship between the Fe concentration and either local rainfall or water temperature. Goreau pointed out that, because the Fe was likely to be detrital in origin and related to variables such as water turbidity, resuspended sediments, and runoff from high rainfalls and land erosion, the interpretation of Fe concentrations required a knowledge of temporal and spatial variations in suspended sediments in the water body. Fe:Ca ratios varied erratically throughout the *Montastrea* skeleton, and Goreau concluded that the absence of a correlation with rainfall suggested that the included detrital components, reported by Barnard *et al.* (1974), did not provide a direct measure of suspended terrestrial sediments resulting from runoff after high rainfall events.

Concentrations of elements which could indicate inclusion of terrigenous particulates vary widely between studies and sampling locations. For example, in *Montipora* spp. from Jamaica, Goreau (1977b) reported that Fe was in the range 363 - 513 ppm and Al at the limit of detection (c. 125 ppm). In contrast, St John (1973, 1974) reports Fe concentrations of 2.0 $\pm$ 14 ppm (n = 26; Poritidae (*Porites, Goniopora*)) and 0.74 $\pm$ 0.81 ppm (n = 141; Acroporidae (*Acropora, Montipora*)) at Heron and Wistari Reefs, GBR. Similarly, Martin (1984) reported Fe concentrations of 5.9 ppm in *Porites* (n = 1) and 1.5 ppm in *Acropora* specimens (n = 5) from Fitzroy Reef, 25 km southeast of Heron Reef. Fe concentrations in *Acropora* spp. samples from Lizard Is, GBR were about 6 times those at Heron/Wistari.

Shen and Boyle (1988) present no data on Fe, Al or Si concentrations in coral skeleton. They suggest that Fe is aragonite lattice compatible, but that contamination is likely to make Fe analyses, for palaeochemical reconstruction, difficult.

Budd, Mann and Guzman (1993) report the results of a study of insoluble residues within reef coral skeletons. They used four massive coral species collected from seven sites along the Caribbean coast of Panama. At least five evenly-spaced 2.5 g samples were cut from each coral head and processed using the methods described in Cortes and Risk (1985). After drying, crushing and weighing, acid insoluble organics were oxidised in sodium hypochlorite and the residue digested in 1N HCl.

Variations in the insoluble residue concentrations were analysed as follows:

- among colonies within localities for each species
- within colonies over a 20 year period
- among localities within species
- among species
- between insoluble residue concentration and skeletal extension rate.

These workers found that the amount of insoluble residue trapped within coral skeletons differed between environments. However, the concentrations of insoluble residue were low (Table 7.1.1) and varied widely so that subtle changes in terrigenous sedimentation could not be detected. Insoluble residue at their sample sites is generally in the range 0.1 - 1.0 % by weight. Simple correlation of residue concentration with sedimentation rate was considered tenuous except under extreme conditions. They conclude that insoluble residue concentrations cannot be used unequivocally in environmental interpretation until more is known about tissue damage, polyp behaviour, and their effects on sediment incorporation.

Species	No. of samples	Mean	Std. Dev.
Diploria strigosa	125	0.271	0.151
Montastraea annularis	129	0.342	0.170
Porites astreoides	125	0.320	0.168
Siderastrea siderea	129	0.232	0.170

Table 7.1.1
Insoluble residue (weight %) in nearshore corals, Caribbean coast of Panama (Budd *et al.*, 1993).

Shen and Boyle (1988) attribute the quite large differences in skeletal trace element concentrations between their results and those of some previous workers to sample contamination due to inadequate pre-treatment of the samples. Consequently, the results and conclusions of earlier work where sample preparation did not meet the criteria of Shen and Boyle (1988) must be viewed with some reserve.

The available evidence shows that fine sediments are incorporated into coral skeletons, and that, in some cases, this sediment is terrigenous in origin. Reported concentrations of elements and residues associated with terrigenous sources vary widely. There is as yet no clear evidence of sediment concentrations being directly linked to geomorphic processes.

Factors influencing particulate inclusion: At the time this research commenced, little was known of the mechanisms by which sediments were incorporated in corals, or of the controls on biological mediation of sediment inclusion. Since that time the results of several studies relevant to these mechanisms have been published, and are included in the following review.

For sediments in coral skeletons to provide a time series of suspended sediment concentrations, and thereby of catchment sediment yields, two conditions must be met. Firstly, sediment must be incorporated into the skeletal material as calcification is occurring and, secondly, sediment in the water column must be excluded from the interior of the skeleton after calcification has taken place. Both of these conditions must be met in order to obtain a high quality record.

1. Sediment inclusion during calcification: Corals have been shown to be capable of shedding sediments (Hubbard and Pocock, 1972; Bak and Elgershuizen, 1976; Fisk, 1981; see below) and to be capable of adapting to changing environmental conditions, eg. metal concentrations, light and temperature levels (Harland and Brown, 1989; Dustan, 1982; Wellington and Glynn, 1983; Buddemeier and Kinzie, 1976; and other literature cited therein). Furthermore, substantial diurnal variations in calcification rates, linear extension rates and crystal morphology have been documented (Barnes and Crossland, 1978; Gladfelter, 1982; Le Tissier, 1988). Le Tissier (1988), using qualitative EDX micro-analysis, showed that the elemental spectra of skeleton deposited at night differed from that during the day. These results suggest that metabolic status of the coral, which varies through time, is likely to be a significant control on particulate inclusion processes. The physiological response of corals to the synergistic effects of combinations of stress at the time of a sedimentation event are also likely to affect biologically-mediated process rates. For example, at a time when high sediment concentrations of fluvial origin were experienced by a coral colony, additional stress from fresh water, nutrients and algal competition and bottom sediment resuspension would also be likely. Clearly, biologically-mediated sediment inclusion rates are likely to be related to environmental conditions in a complex way.

More importantly, in order for a sediment record to be extracted from coral skeletons, the process of incorporation must occur as a biologically-mediated process, rather than simply by deposition on tissue-damaged areas and subsequent overgrowth, as suggested by Barnard *et al.* (1974). By microscopic examination, Barnard *et al.* (1974) showed that arched dissepiments covered cavities in which detritus had been trapped. The arching of the dissepiments suggested that the cavities were sealed by living polyps after the sediment entered. It was assumed that the sediment must have entered while the polyp was either damaged or destroyed. This assumption was based on the known sediment shedding capability of corals. If sediment incorporation occurs by deposition and overgrowth, then the sediment inclusion time series is principally a record of tissue damage.

Davies (1991) suggested a method by which the sediment incorporation mechanism/s could be determined. The method, which uses TiO_2 as a tracer, is described in detail in Davies (1992; in prep.). His results show that sediment inclusion is predominantly through areas where tissue damage had occurred, confirming the suggestion of Barnard *et al.* (1974).

Davies observed another possible mechanism for incorporation of sediments. TiO_2 particles, to which the corals had been exposed, remained within the coral tissue for four months after ingestion. Davies suggests that, rather than expel these particles, a more efficient means of removal would be simply to leave them behind, incorporated into the skeletal aragonite, as the tissue moves upward. This mechanism appears to be particle-size specific (< 10 μm) and, because of the minimum four-month retention period, would not be chronologically correct with respect to ambient concentrations.

Another mechanism of sediment incorporation was recently suggested by Brown *et al.* (1991). When coral tissues temporarily retracted under conditions of stress, iron compounds were deposited on exposed skeletal spines and bound by mucus. Coral recovery and renewal of calcification resulted in their incorporation into the skeletal matrix. Brown and co-workers recorded no detrital inclusion during the tissue retractions observed. However, they note that polyp retraction is a response to a variety of stresses, and suggest that, on any occasion that retraction occurs and mucus-covered spines are exposed, there is potential for skeletal inclusion of particulate or precipitated material.

2. Sediment inclusion after calcification: Post-calcification sediment inclusion takes two forms. It can occur both at the colony surface following tissue damage or within the colony following boring by endolithic organisms.

Tissue damage leading to sediment inclusion at the colony surface may have several causes (Davies, in prep.). Grazing by fish is one possibility, although Davies dismisses this cause on two grounds. Firstly, the extent to which scarids actually feed on live coral tissue is controversial (Hutchings, 1986) and secondly, the parrotfish functional group most likely to cause severe tissue damage, the 'excavators' (Bellwood and Choat, 1990), is rare or absent from the inner GBR (Russ, 1984).

Tissue damage has also been attributed to several direct and indirect effects of suspended and deposited sediments. These include abrasion by sediments carried on strong currents, light reduction, smothering by physical blocking of oxygen-carrying waters, damage by microbial action increased by high sediment concentrations, and the energy drain required for sediment shedding (Hodgson, 1990, and references therein), and to the interactive effects of high sediment and nutrient concentrations and algal overgrowth. Another factor is damage caused by *Acanthaster planci* which is likely to have been patchy in both time and space.

Porites skeletons have two structural characteristics of critical importance to the pattern of sediment inclusion following boring by endolithic fauna. Firstly, sheet dissepiments occur over wide areas of the skeleton, inhibiting, although apparently not entirely preventing, vertical movement of detrital material within the skeleton. These dissepiments form at intervals of about 30 days (Barnes and Lough, 1992) and no further calcification takes place within the calice after they have formed. Consequently, a minimum resolution of about monthly intervals, with no contamination during adjacent months, is a realistic expectation of skeletal records from these corals. Secondly, the walls of the calice are porous. This porosity allows contaminants to move laterally through the skeleton once they are introduced through any site of skeletal damage, generally by boring organisms. Coral skeletons in nearshore environments are particularly prone to damage by endolithic fauna (Sammarco and Risk, 1990) and, therefore, to skeletal contamination by this means.

Solutions to these problems are not simple. There appear to be at least two mechanisms of biologically-mediated sediment inclusion at the colony surface, one observed and the other inferred, one requiring a prior stress-response and the other in which the physiological processes are unknown. Sediment inclusion at the colony surface may also occur if sediment deposition follows tissue damage which may be the result of one or several causes. In addition, further inclusions may occur via the burrowing of endolithic fauna.

The model of *Porites* skeletal growth proposed by Barnes and Lough (1993) implies chronological errors of about 30 days associated with skeletal inclusions, although Gagan *et al.* (1993a, b) report a 7 day resolution. However, these are minor compared with the > four month period in the mechanism suggested by Davies (in prep.). The post-calcification inclusion mechanisms also imply patchiness in the distribution of inclusions. In coral cores, which are the only practical method of obtaining long-term sclerochronological records, it will not always be possible to determine the cause of high sediment concentrations in a particular band. This is a relatively minor problem in short-term studies of a few decades in which the entire colony can be analysed. Although scrupulous cleaning of the coral skeleton, as described by Shen and Boyle (1988), may remove the post-calcification inclusions, uncertainties remain regarding the processes of biologically-mediated inclusion, the role of physiological response to stress and the synergism of environmental stresses in biological process rates.

Efficiency of sediment exclusion: The ability of corals to shed detrital material deposited on them has been well documented. The importance of sediment shedding lies in the ability of competent shedding species to colonise areas of relatively high sediment deposition rates, such as has been shown to be the case with the abundance of *Montastrea cavernosa* on high-sedimentation reefs, and the relative abundance of *M. annularis* on reefs with low sediment deposition rates (Lasker, 1980). The ultimate consequence of sediment accumulation is the build up of an anoxic deposit which kills the underlying tissue (Lasker, 1980). Fisk (1981) identified five mechanisms of sediment rejection in specimens of *Heteropsammia cochlea* and *Heterocyathus aequicostatus*.

The capacity for, and efficiency of shedding varies between species, between intra-specific growth forms and by sediment particle size and quantity. Hubbard and Pocock (1972) reported that 17 of 26 coral species tested were most efficient at shedding fine sediment, five species were equally efficient across the size range (< 63 µm to 2 000 µm) and one was better at removing coarse sediment than fine. Two species were very inefficient at sediment removal. Four species of *Porites* were included in the experiment and all were very efficient at sediment removal, particles < 250 µm by tentacular manipulation of individual particles and those < 63 µm by ciliary action. Their ability to remove coarse sediment was poor. Experiments on fungiid corals (Schuhmacher, 1977) indicated no difference in sediment shedding efficiency between carbonate and silicate sand.

Calical angle is also important. Hubbard and Pocock (1972) found that a polyp positioned with the calice inclined shed sediment twice as fast as one placed horizontally. Lasker (1980) observed that if polyp walls or the colony surface of *M. annularis* were steeply inclined particles simply rolled off. Experiments on the solitary coral *Scolymia cubensis* with calices inclined at 0^{o}, 35^{o} and 75^{o} to the horizontal showed that increased angle resulted in increased sediment shedding regardless of sediment size (62, 250 or 2 000 µm) or the polyps activity phase (quiescent or feeding) (Logan, 1988). The complexity of the relationship between coral morphology and passive and active sediment shedding is a feature of the results of virtually all studies examining this aspect of coral behaviour. Morphology is important at three levels:- the colony, the surface and the calice (Bak and Elgershuizen, 1976).

It is also possible that coral polyps may induce greater sedimentation in their immediate vicinity. Sponaugle (1991) and Sponaugle and Le Barbera

(1991) showed that, for the tropical gorgonian *Pseudopterogorgia acerosa*, water velocity reductions of 40 % to 80 % (varying with mainstream velocity) occurred due to polyp flexion. Greater reductions occurred due to whole colony and polyp flexion combined, but whole colony flexion is not relevant to hard corals. As feeding rates of *P. acerosa* are low at both low and high velocities, and high at moderate (10 - 15 $cm.s^{-1}$) velocities, these velocity reductions at the polyp surface increase feeding success over a wide range of velocities. It follows that sediment deposition on the coral surface may also be increased by the hydrodynamic effects of polyp flexion.

The effects of stress on reef corals, including sedimentation stress, have been reviewed by Johannes (1975), Brown and Howard (1985) and Hatcher, Johannes and Robertson (1989). Sedimentation stress results from reduced illumination (causing reduced respiration and productivity, and reduced photosynthesis by, and loss of, zooxanthellae) and the physical effects of particle deposition (burial, abrasion and the metabolic cost (Dodge *et al.*, 1974) of sediment shedding). Larval settlement, growth, feeding and reproduction rates may all be inhibited. Coral response to sedimentation is variable between species and within colonies with respect to both sediment shedding (Bak and Elgershuizen, 1976) and zooxanthellae loss (Rogers, 1979).

The pattern which emerges is one in which skeletal incorporation of both solutes and particulates varies both between and within colonies and is mediated directly and indirectly by environmental variables, the range, perseverance and type of which are altered by human impact. For example, increases in sediment concentration due to dredging or land use change can result in zooxanthellae loss which, in turn, may lead to changes in the partition coefficients for some solute inclusions. If it is necessary for polyp damage or death to occur before particulates can be included in the skeleton, then this "environmental index" may only operate above some stress threshold. This level of stress may be induced by the particulates themselves or by an independent effect, either natural (e.g. extreme temperatures or low tides) or artificial (e.g. heavy metal pollution).

The patterns outlined in this brief review suggest that sediment in corals may not be a good general indicator of suspended sediment concentrations. However, by extraction of a vertical core from a single specimen of a large massive coral, such as a *Porites* colony, variations between species, growth orientation, and sites is minimised or eliminated.

<u>*Sampling and analytical techniques:*</u> By dissolving a relatively large sample of coral a gravimetric determination of the sediment concentration can be

made. However, such an analysis will not usually permit fine resolution in sampling and is invalid if particulates of marine origin are included.

In this study, the basis of the analysis of skeletal inclusions was their relationship with the fluorescent bands and, in turn, their relationship with stream flow. Isdale (1984) indicated that the fluorescent bands responded to streamflow events on a scale of weeks to months and the observations of multiple fluorescence peaks in years of multiple flood peaks (Chapter 6.2) lends some support to this. Therefore, in order to maximise the resolution of the inclusion time series, a sampling interval similar to the potential resolution period of the fluorescent bands was necessary, along with a technique for sample extraction at that scale. Given skeletal extension rates of about 15 $mm.yr^{-1}$ and the scale of variation in the fluorescent banding (Chapter 6.2) a sampling increment of between 1 and 2 mm was appropriate. Such sampling required some degree of precision. Several approaches to sampling coral skeleton have been reported, including use of a coarse-toothed metal file (Dodge and Thompson, 1974), a small chisel and hammer (e.g. Nozaki *et al.*, 1978), a masonry drill (Fairbanks and Dodge, 1979), a thin-bladed gem-cutting saw (Goreau, 1977 a, b), diamond-bit dental saw (Benninger and Dodge, 1986), a surgical saw and fracturing with forceps (Land *et al.*, 1977) and a rocksaw, bandsaw and jewellers saw (Shen and Boyle, 1987). The method which is appropriate varies according to the sample volume required. An additional factor to be taken into account is the complex morphology of the growth surface which varies both within and between annual growth bands (Fig. 6.2.1).

This investigation proceeded in two stages. First, a suite of methods was used to measure particulate characteristics in the Rockingham Bay corals. These methods included X-ray diffraction (XRD) analysis, scanning electron microscopy (SEM) with electron dispersive X-ray emission (EDX), and electron microprobe analysis. None of these methods lends itself to band sequence measurement so an alternative technique, comparable with the 'Fluorac' system, was sought. Such a method would be expected to derive mineralogical and/or elemental data from within c. 0.1 mm of the sample surface, measure over an area equivalent to c. 1 month of coral growth and would be capable of precision stepping along an intact section of coral core.

The ion beam analysis facility at the Lucas Heights Research Laboratories of the Australian Nuclear Science and Technology Organisation (ANSTO)/Australian Institute of Nuclear Science and Engineering (AINSE) meets these criteria reasonably well. This equipment, described in detail below (7.1.2.2), measures elemental concentrations of samples mounted on a 1 m long sample stick, can be stepped at increments $\geq$ 0.1 mm, and utilises an ion beam of 2 mm diameter with an estimated penetration depth of c. 50 μm in $CaCO_3$. In this study, ion beam analysis was used to investigate skeletal concentrations of elements derived from terrigenous sediments.

7.1.2 Analysis:

7.1.2.1 Preliminary investigations:

Preliminary investigations of coral skeletal material in samples from Bedarra Island were undertaken to confirm the presence of terrigenous detritus. Dissolution of samples from two small colonies from the Bedarra Island fringing reef resulted in insoluble residues in the range 0.1 - 1.0 % by weight, consistent with the concentrations measured by Budd *et al.* (1993). Microscopic examination showed that these particulates were clay and fine silt sized. Results of the preliminary investigations are summarised below:-

(i) X-ray diffraction (XRD) analysis: 20 g samples of coral skeleton from Bedarra Island corals were dissolved in ethylenediaminedinitrilotetracetic acid (EDTA) solution, the supernatent decanted off and the residue filtered through pre-washed Whatmans 42 (5 μm) filter papers. EDTA solution was used as it does not dissolve or alter clays, as can occur with dissolution in acid at pH < 3.5 (Glover, 1961). Note that deflocculated clays will pass through these filters.

X-ray diffraction analysis of the residues retained on the filter papers was undertaken using a Siemens diffractometer (Dept. of Geology, Australian National University; 40 kv, 20 mA, $4^{o} < 2\Theta < 30^{o}$). A section of filter paper was attached to the glass slide using double sided adhesive tape. Blanks of clean filter paper were tested and found to give no specific X-ray peaks, although an increase in the background curve was evident, possibly due to the X-ray beam penetrating to the glass slide. The d-spacings of the emission spectra were reduced by 0.8 % due to the thickness of tape and filter paper.

The coral skeletal residue included terrigenous minerals, including quartz, kaolin and accessory feldspars, with less illite and accessory chlorite (Fig. 7.1.1). The higher quartz:kaolin peak height ratios, by comparison with Tully River samples (Table 7.1.2), could be explained by the influence of island sediment sources as direct runoff and/or wave resuspension, or by the differing pore size of the filter papers used.

A conspicuous broad band of high background in the range $16^{o} < 2\Theta < 28^{o}$) is interpreted as particulate amorphous silica (J. Caldwell, 1989: pers. comm.). This may be derived from debris of degraded marine invertebrates or diatoms and may represent resuspended bottom sediments.

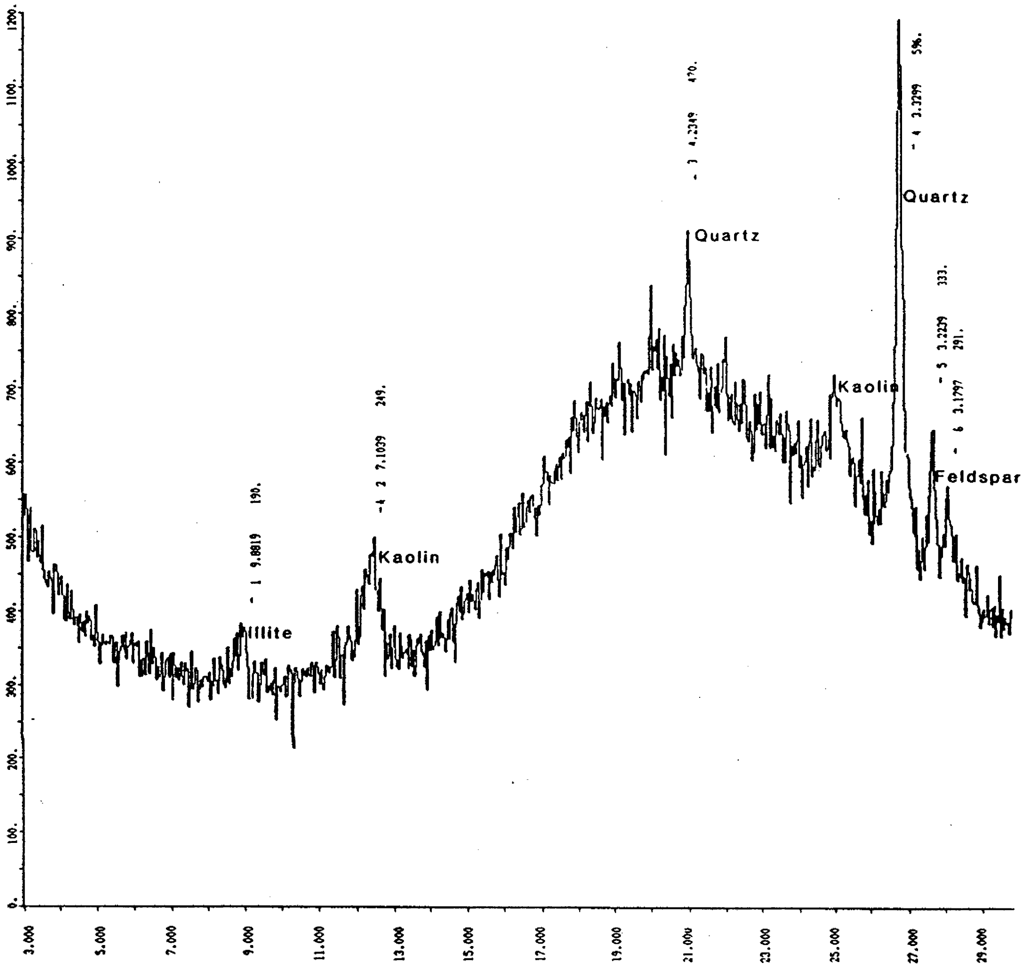


Fig 7.1.1
X-ray diffractogram for the dissolution residue of coral skeleton from the Bedarra Island fringing reef.

	River residue	Coral residue
Q (21 2Θ°): Ka (12.5 2Θ°)	0.12	1.1
Q (26.8 2Θ°): Ka (25 2Θ°)	0.32	5.2

Table 7.1.2
Peak height ratios of quartz and kaolin for typical XRD spectra of Tully River water and Bedarra Island coral dissolution residues.

(ii) <u>Scanning electron microscopy (SEM) with electron dispersive X-ray emission (EDX) analysis:</u> Samples of coral skeleton from Bedarra Island were ultrasonically washed, dissolved in dilute acetic acid, the supernatant decanted off and the remainder filtered through pre-washed Whatmans 42 filter papers. Samples of Tully River waters were similarly filtered through Whatmans 42 filter papers. Samples of coral skeleton from Bedarra Island were ultrasonically washed in dilute acetic acid.

Segments of these filter papers and the coral samples were mounted on stubs and gold coated for SEM/EDX analysis of elemental composition using a Cambridge scanning electron microscope (Electron Microscopy Unit, Australian National University). Beam energies of 20 and 30 kv were used.

The elements of interest are Si and Al, because XRD analysis showed that clay and quartz were present, and Fe because iron oxides from soil particulates are also expected. X-ray spectra of Tully River sediments (Fig. 7.1.2a) are similar to those of coral residues (Fig. 7.1.2b) for these elements. Four determinations of each were made, and peak area ratios indicate that Si concentrations are higher, relative to Al and Fe, in the coral residues than in river sediments. This is consistent with incorporation of biogenic marine silicates into the coral skeleton, as also suggested by the XRD results. Fe concentrations are lower in the coral residues, relative to both Si and Al (Table 7.1.3).

	River water residues		Coral residues	
	$\bar{x}$	s.d	$\bar{x}$	s.d.
Si:Al	2.64	0.36	4.78	0.28
Si:Fe	3.35	1.66	14.75	1.50
Al:Fe	1.34	0.75	3.09	0.29

Table 7.1.3
Elemental peak area ratios for river water and coral dissolution residues (SEM/EDX analysis).

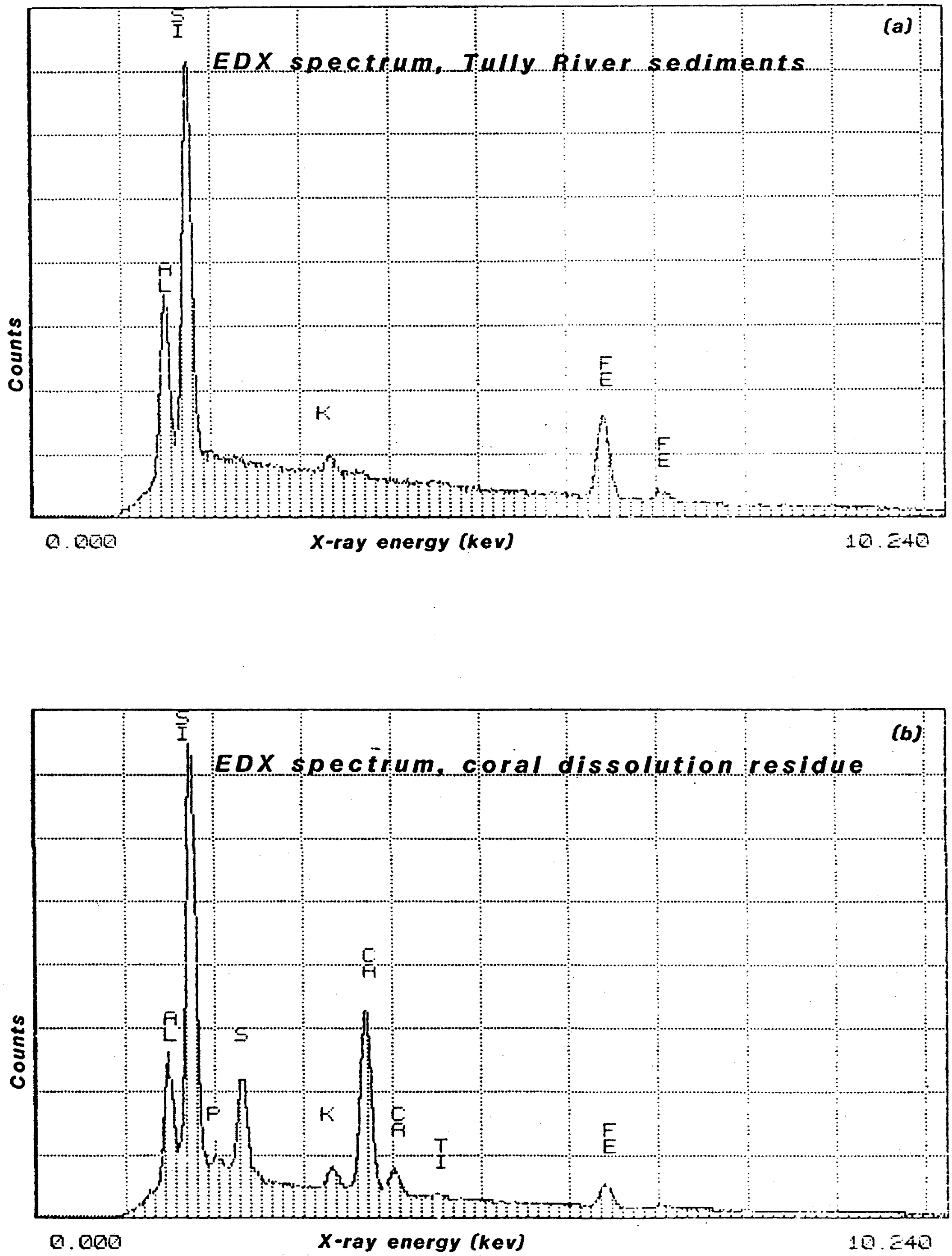


Fig 7.1.2
SEM X-ray spectra for Tully river sediments and the residue of coral dissolution.

The major elements observed in the filter paper residues were essentially undetectable in X-ray spectra for the bulk coral skeleton samples. Neither was there any discernible difference between spectra for sections of coral skeleton which appeared 'clean' (Fig. 7.1.3a) and those which were discoloured, possibly by detrital inclusions (Fig. 7.1.3b). X-ray maps showing spatial variation in sources of X-rays at energies appropriate for Al and Si (Fig. 7.1.4) indicate no clustering of sources for either clean or discoloured samples. Therefore, any terrigenous detritus incorporated into corals is likely to be distributed throughout the skeleton, rather than concentrated in particular locations. In fact, the X-ray maps are showing the distribution of background X-ray emissions at Al and Si energies (Fig. 7.1.3). EDX analysis of much smaller sections of skeleton at much higher magnifications did not reveal any concentrations of Si, Al or Fe sources which could be interpreted as concentrations of inorganic particulates. The growth surface of the coral colony, and the interior of the skeleton where coral tissue and filamentous algae occur have similar spectra to determinations deeper in the skeleton, with the exception that higher Cl concentrations are apparent below the surface in areas of coral tissue and filamentous algae. This is attributed to the use of chlorine bleach to kill and deodorise the small colonies from Bedarra Island which were used for these analyses. No chlorine bleach was used on the coral cores.

Elements identified from coral residue using SEM/EDX analysis (Al, Si) are consistent with the composition of the dominant minerals (quartz, kaolin) identified in the XRD spectra. The presence of Fe is not expected from the mineralogy, but is consistent with the presence of soil particulates. EDX spectra for Tully River suspended sediments and for Bedarra Island coral residues are consistent with respect to the presence of Al, Si and Fe.

(iii) Electron microprobe analysis: Elemental composition of the coral skeleton was investigated using the electron microprobe facility at the Research School of Earth Sciences, Australian National University. Samples were cut using a milling machine and ultrasonically washed in dilute acetic acid. For accurate elemental determinations using the microprobe polished thin sections are required which is difficult with porous corals and the results given are only semi-quantitative.

Trace element concentrations in Bedarra Island coral samples indicated that Si, Al and Fe were generally in excess of 150 ppm, with Fe generally higher than Al and Si. Al concentrations were positively correlated with Si ($r^2=0.70$; $n=11$; $p<0.05$), although this was not the case with Fe. The highest

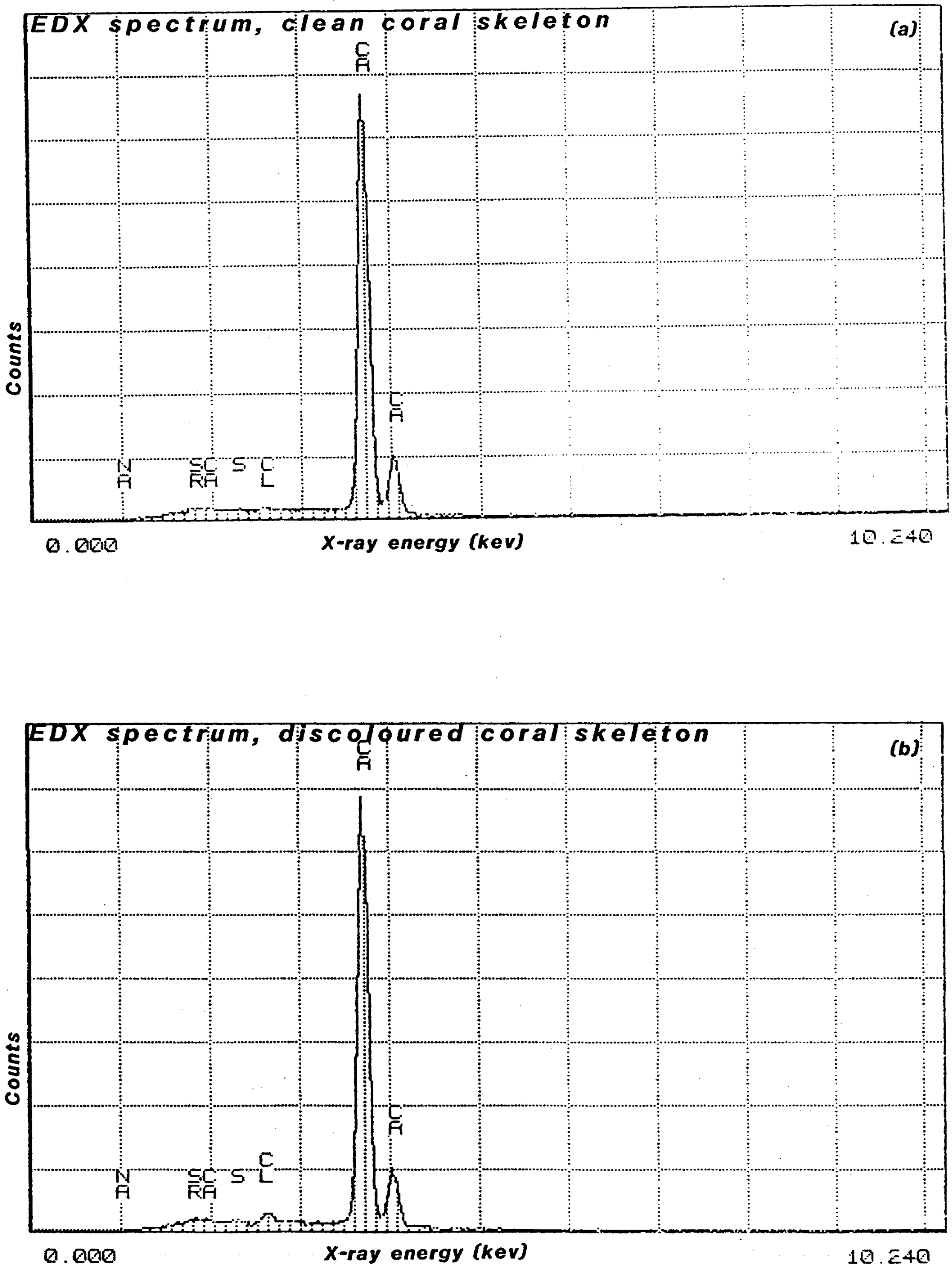


Fig 7.1.3
SEM X-ray spectra for 'clean' and 'discoloured' coral skeleton.

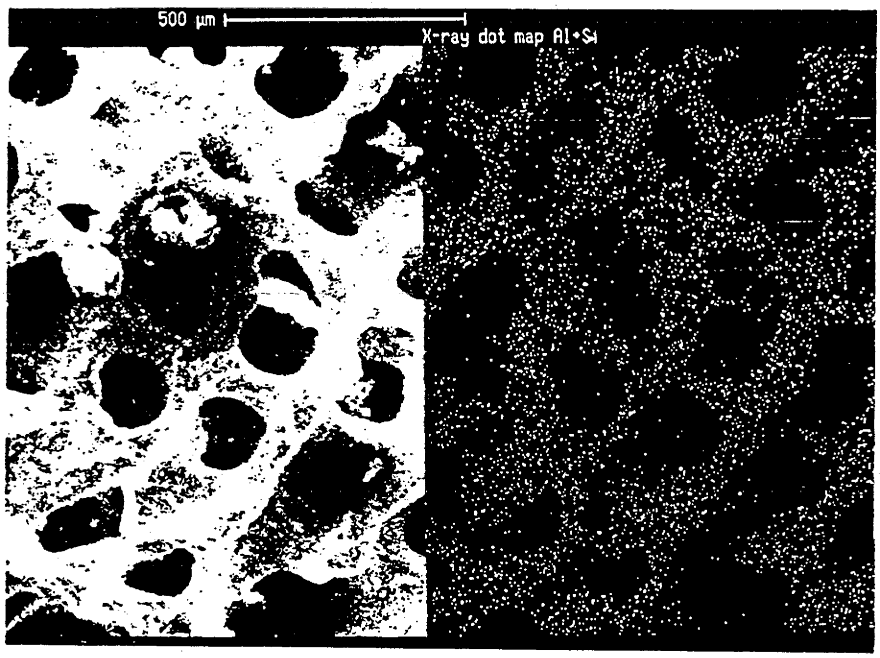


Fig 7.1.4
X-ray maps showing distribution of Al and Si sources in coral skeleton.

Si, Al and Fe concentrations were generally associated with areas of skeleton with strong UV fluorescence.

These results, from intact coral skeleton, are consistent with the XRD analysis of residues, in terms of the elemental composition of the clay minerals identified, and with the EDX spectra for residues. However, Fe is apparently present at higher concentrations, relative to Al and Si, in the intact coral skeleton than in the insoluble residue. This may indicate a significant presence of Fe precipitated from solution, rather than in particulates, in the coral skeleton, although no firm conclusion can be reached because of the semi-quantitative data. The source of the Fe is unclear, but may be some combination of soil particulates, Fe in solution, or Fe associated with fulvic acids and/or other humic solutes and colloids.

Interpretation: These preliminary analyses show that massive coral skeletons from fringing reefs offshore from the Tully River at Bedarra Island contain acid-insoluble residues which are elementally and mineralogically consistent with a fluvial source, possibly the Tully River. The Al and Si EDX peaks (Fig. 7.1.2), the Al and Si concentrations determined using the electron microprobe and the positive correlation between them, and the kaolin XRD peaks (Fig. 7.1.1) are consistent with the inclusion of alumino-silicate clays from a terrestrial source in the coral skeleton. Al and Si X-ray sources are ubiquitous in the coral skeleton (Fig. 7.1.4), although they relate to background rather than identifiable peaks on the spectra. Elementally, the Al is particularly diagnostic, given the absence of primary Al-bearing particulates in the marine environment.

Si is not diagnostic of terrigenous quartz, because of the broad peak in the XRD spectra (Fig. 7.1.1) attributed to amorphous silica with a probable marine origin. Simple gravimetric determinations of the acid-insoluble residue are not an adequate measure of the terrestrial input to the nearshore marine environment because part of the insoluble residue may be of biogenic marine origin. Contrasting kaolin:quartz ratios in the coral residues and the river sediments (Table 7.1.2) may indicate selective deposition and resuspension of kaolin and quartz, a local (island) sediment source, or a filter paper pore-size effect.

Fe concentrations are not correlated with Al or Si which raises some doubt as to its veracity as a terrigenous inputs recorder. Although Al, Si and Fe together were associated with terrigenous smectite by Barnard *et al.* (1974), there is no evidence of this mineral in the XRD spectra. However, included Fe could be derived directly from soils of the Tully catchment and the adjacent islands, indirectly from resuspension, precipitated from solution, or co-precipitated with fulvic and humic acids. The results of the preliminary investigations, with respect to the potential of Al, Si, and Fe as recorders of terrigenous inputs, are summarised in Table 7.1.4.

The apparent concentrations of elements associated with the alumino-silicates and sesquioxides characteristic of wet tropical catchments are sufficient to encourage growth-band analysis using the Lucas Heights PIXE/PIGME facility.

Element	Result: Encouraging	Result: Discouraging
Al	Present in river sediment, coral residue and skeleton; Consistent with mineralogy; + correlation with Si; Concentration > 150 ppm.	
Si	Present in river sediment, coral residue and skeleton; Consistent with mineralogy; Concentration > 150 ppm.	Biogenic marine Si present?
Fe	Present in river sediment, coral residue and skeleton; Concentration > 150 ppm.	Not consistent with mineralogy; No correlation with Si or Al; Several possible sources:- particulate, precipitation from solution, co-precipitation with organic solutes and colloids.

Table 7.1.4
Summary of characteristics of elemental signatures in coral skeleton relevant to their potential as recorders of terrigenous inputs.

7.1.2.2 *The PIXE method:*

General principles: As suggested above (7.1.1), the proton induced X-ray emission (PIXE) analysis method, established at the Lucas Heights Research Laboratories, has a number of potential advantages in the study of skeletal inclusions in massive corals, including the ability to measure elemental concentrations on core sections of up to 1 m in length, to step down a core at selected increments utilising an ion beam of a selected diameter appropriate to the analysis with an estimated penetration depth in skeletal $CaCO_3$ of < 50 μm. Further advantages include a multi-element analysis capability with a relatively short time period required for each determination (generally < 5 minutes) and analyses which are only very locally destructive.

The basic principles involved in the PIXE method are as follows. A proton beam is directed at the target (sample for elemental analysis). When the proton is slowing during its passage through the target, ionisation produces X-rays (Fig. 7.1.5(a)). The X-rays have energies characteristic of the atom from which they were emitted. An appropriate detector is used to record the X-ray spectra from which the elemental composition of the target can be calculated. A solid-state Si(Li) detector is used which is sensitive over a working energy range of about 1 - 100 keV, effectively setting the lower sensitivity limit in the vicinity of Na or Al (Cohen and Clayton, 1989). Detector efficiency, which varies across the energy range (Cohen and Clayton, 1989), must be calibrated.

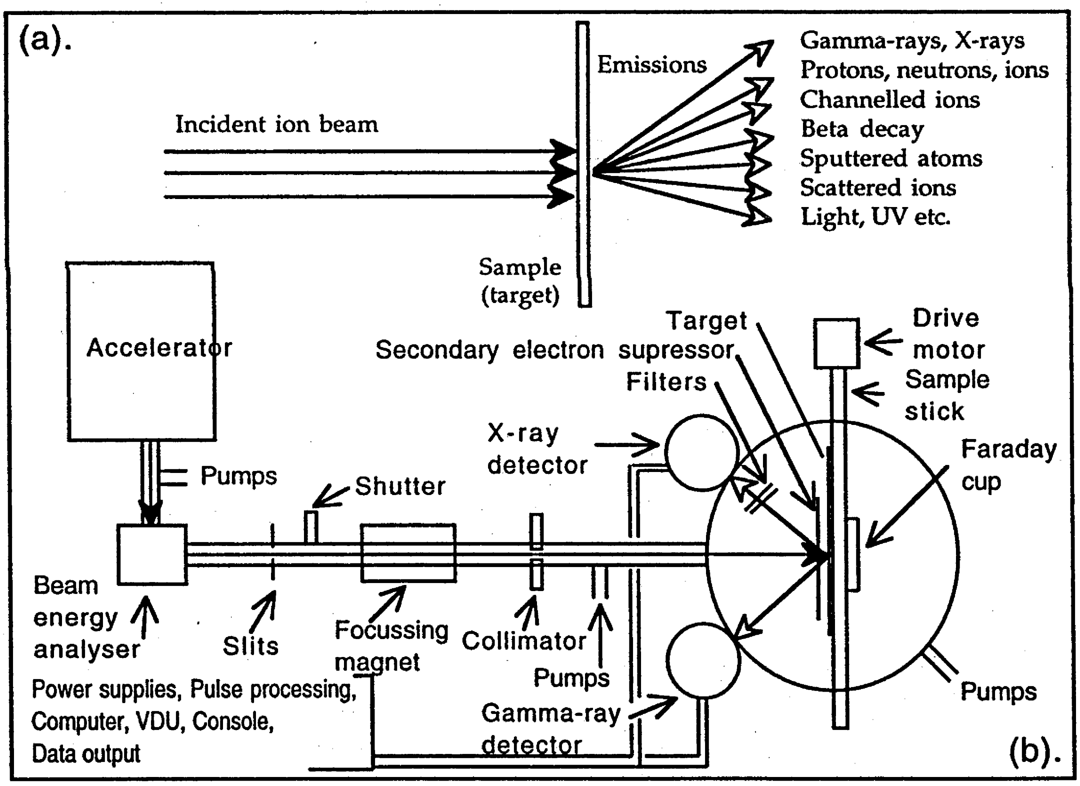


Fig. 7.1.5
Schematic diagrams showing the interaction of the ion beam and the sample (a), and the configuration of the ion beam analysis facility (b).

The beam energy used for elemental analysis is generally in the range 1 - 5 MeV. In the case of the Lucas Heights facility the ion beam is generated by a 3 MeV Van de Graaf positive ion accelerator. The beam is directed to the target by a series of magnets and electrostatic deflector plates, and collimators define the beam. Beam uniformity is important in obtaining a uniform response over the entire area chosen for the target. Substantial deviations from uniformity would lead to potential errors in interpretation if targets were heterogenous. The target is surrounded by a Faraday cup arrangement, connected to a current integrator. The current integrator sums the number of protons falling on the target and when a predetermined charge is reached the run is terminated.

Useful overviews of the PIXE method are given by Johansson and Johansson (1976) and Cohen and Clayton (1989).

Filters: In cases where the target spectrum is dominated by a particular element/s, a filter can be placed between the target and the detector in order to enhance the count rate from the energy range of interest. For targets with constituents over a wide range of atomic weights this may permit the entire range of constituents to be analysed in one determination. In other cases one determination with a filter and another without may be necessary. Commonly used filter mediums include Al, Be, Mylar, Perspex, Kapton and graphite with a pinhole orifice. Using the attenuation coefficients of Veigele (1973), Clayton (1986) has derived transmission formulae for these materials which are incorporated into X-ray energy spectrum analysis.

Signal at the detector: There are several factors, apart from the target composition, which affect the PIXE spectrum. These are as follows:

Brehmsstrahlung: Secondary electron brehmsstrahlung refers to the radiation released as particles, accelerated after collision with the proton beam, decelerate as they pass through the target volume. This energy (as recorded at the detector) is not specific to any component of the target, is at a maximum at energies < 10 keV and forms a background to the energy spectrum which can be accurately calculated and corrected for. Other sources of background energy are frequently six orders of magnitude less than secondary electron brehmsstrahlung (Folkmann *et al.*, 1974) and are not considered here.

Alpha and beta peaks: X-rays arising from proton interactions with K, L and M electron shells of a target atom can, in a modern Si(Li) detector, be detected for elements from Na, Zn, and Dy upwards, respectively (Cohen and Clayton, 1989). In this study only one element of interest (Sr) occurs above the threshold at which L X-rays can be detected (Zn) and none above the threshold for M X-rays. Consequently, only K X-rays are considered further. When the electron which replaces the displaced one comes from the

L shell the X-ray is referred to as K_α and has a slightly lower energy than if the electron comes from the M shell (K_β) or from a shell further out. K_α and K_β X-ray energies are similar for a given element, distinct from those for other elements and are readily incorporated into the analysis of the X-ray spectrum.

Escape peaks: Escape peaks appear on the PIXE spectrum as a result of the interaction of the target atom and a silicon atom in the detector causing the emission of a Si X-ray which then escapes from the detector. The interaction has a known probability and results in an energy peak at the detector 1.74 keV lower than would be the case for complete absorbtion of the original X-rays energy. The ratio of the escape peak and and parent peak energies is a function of X-ray energy, is known and the resulting error can be removed during data processing (Cohen and Clayton, 1989).

Sum peaks: Sum peaks are produced when two pulses arrive at the detector amplifier at about the same time, in which case they may be recorded as one pulse, the energy of which is the sum of the two. Sum peaks are also routinely removed from the spectrum during data processing (Clayton, 1986).

Spectral analysis: The software devised by Clayton (1986) for analysing PIXE energy spectra treats the spectrum as "modified Gaussian peaks on a background". A non-linear least-squares fitting procedure is used to determine the peak area for each element. The background components discussed above are fitted and removed from the spectrum after first correcting for detector efficiency.

An error estimate is provided by the standard deviation of the peak area, calculated as:

$$SN = \sqrt{(N+2B)}/N, \qquad \text{[Eqn. 7.1.1]}$$

and a minimum detection limit (M.D.L) is defined as:

$$\text{M.D.L.} = N \geq 3.29\sqrt{B}, \qquad \text{[Eqn. 7.1.2]}$$

where: N = peak area for a given element
S = standard deviation
B = background (Clayton, 1986).

Additional spectral analysis can be used to determine elemental concentrations from the peak areas. In this investigation, spectral analysis was limited to peak area determination.

7.1.2.3 *The PIGME method:*

<u>General principles:</u> A disadvantage of the PIXE method is its insensitivity to elements of atomic number $\leq$ 15 (Antilla *et al.,* 1981). This includes Al and Si which are characteristic of clays and quartz. Proton-induced gamma emission (PIGME) analysis is sensitive to the lighter elements and, therefore, when used in conjunction with PIXE, gives a simultaneous multi-element analysis of the target covering most of the periodic table. This obvious benefit of the simultaneous application of PIXE and PIGME methods is offset by the relative insensitivity of PIGME in the analysis of elements above Si (At. wt. = 14) at proton energies in the range 1-5 MeV (Hall and Navon, 1986), the range in which PIXE gives optimum performance. Antilla *et al.* (1981) also point out that PIGME is particularly sensitive to those light elements which have low abundances in nature (eg. Li, B, F), but less sensitive to naturally common elements (eg. O, Si, C). Gamma energies are not necessarily unique to a specific element or isotope, but may be common to several elements.

Unlike PIXE, the PIGME method is relatively insensitive to the problem of light element attenuation (Bird, 1989) and is therefore insensitive to surface topography and requires minimal sample preparation (Borderie, 1980). Given the high variability of the coral surface at scales relevant to ion-beam analysis, this is an important consideration.

The PIGME method is essentially the same as that for PIXE and, for simultaneous determinations, requires only the addition of another detector and appropriate software. A Ge(Li) detector is used for gamma ray detection, sensitive to gamma rays with energies from 0.1 MeV to 10 MeV. In this study only gamma energies > 0.5 MeV were recorded. At LHRL the detector is placed on the opposite side of the beam to the Si(Li) detector (Fig. 7.1.5b).

7.1.2.4 *Coral core processing for the PIXE and PIGME methods:*

<u>Sample selection:</u> Due to limitations of available accelerator time at LHRL, a small set of coral samples was selected. The coral core sites closest to the Tully River mouth (Chapter 6.1) are at Kumboola, Bedarra and Dunk Islands, while Kumboola, Bedarra and Coomb Islands had the highest mean suspended sediment concentrations during the 1990 sampling period (Table 5.3.2), with $\bar{x}$ SSC = 3.6 $\pm$ 2.6, 3.6 $\pm$ 2.2 and 2.9 $\pm$ 1.7 respectively. The top 545 mm of the KUB core was analysed (1955+). Older sections of the coral head were damaged by boring organisms. The upper 310 mm of the BED core was analysed, across the hiatus in growth which was observed in all cores from this coral head. Only a short section of this core was analysed to examine the effects of the break in growth, because of uncertainty as to duration of the

hiatus. The COO core was analysed because of relatively high SSCs in adjacent waters during sampling periods and its long record (c. 1911 at 945 mm). SSCs at Brook Islands ($\bar{x}$ = 1.8 ± 0.29) were the lowest recorded for any site. The upper 310 mm (c. 1962+) of the BRO core were analysed as a contrast with the relatively high SSC at the other sites.
Slices 7 mm and 1.7 mm thick had been cut from each core (except BRO). The 1.7 mm thick slices were chosen for the ion beam analyses with the intention of subsequently undertaking geomechanical analyses which could only be performed on the thin slices. Skeletal fluorescence and density had previously been determined on 7 mm slices from these cores. One 7 mm thick section of the COO core and a 7 mm thick slice of the BRO core were analysed because 1.7 mm slices had not been prepared. The ion beam penetrates to only c. 50 μm depth and the target face of the sample is at the same position relative to the beam regardless of slice thickness, so no variation in the PIXE/PIGME signal due to sample thickness was expected.

Sample preparation: Core retrieval and cutting was described previously (Chapter 6.1). Sections 20 mm wide were cut from the slices which were previously removed from the cores using the milling machine. Each section was ultrasonically washed in dilute acetic acid. No further sample pre-treatment was carried out.

The core sections were mounted on a custom built "sample stick" designed to allow the entire length of section to be stepped through the beam without obstruction. A stainless steel backing was fastened behind the coral section to assist in heat dissipation, particularly for the thin coral slices which were used. Sections of the KUB, BED, COO and BRO cores were analysed using the PIXE/PIGME method.

Measurements: The Si(Li) (for PIXE) and Ge(Li) (for PIGME) detectors are placed on either side of and at 135^{o} to the proton beam. A description and photograph of the target chamber are given in Duerden *et al.* (1984), the general configuration of which is illustrated in Fig. 7.1.5(b).

Proton beam energies of 2.6 MeV (BRO, COO, KUB cores) and 2.7 MeV (BED core) were used and a beam current of approximately 100 nA resulted in a dead time < 5 % of running time (generally 1 % - 2 %). The beam current was varied in order to minimise target damage, to which the thin coral slices were particularly susceptible, and to maintain low dead times. The accumulated charge for each run was 100 μC and running times varied between about 2.5 and 6 minutes according to the beam current used.

The Ge (Li) detector for PIGME determinations was only functional at the time the BRO and COO cores were analysed. The beam energy used is determined by the yield characteristics for the elements of interest, principally Al (Fig. 7.1.6), limited by the ability of the accelerator to maintain energies close to its maximum output.

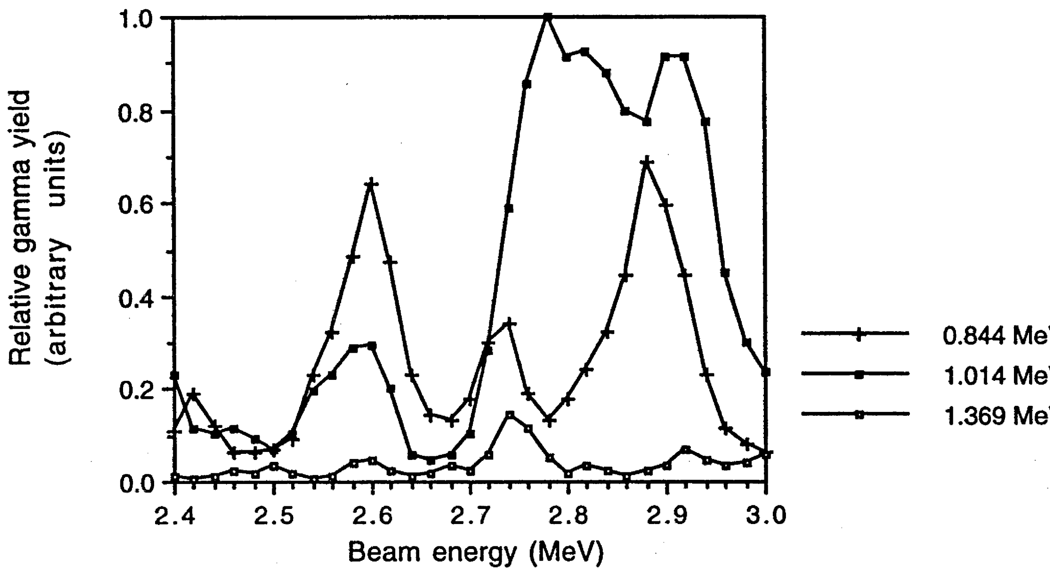


Fig. 7.1.6
Relative gamma yields for the reaction with Al for protons in the range 2.4 - 3.0 MeV (data from Boni *et al.*, 1988).

During the running of the KUB core a 200 µm Mylar filter was used for the PIXE determinations. Al and Si X-ray counts were not statistically significant with this arrangement. Fe counts, though higher, were inadequate for reliable determinations. In order to reduce the magnitude of the Ca peak and thereby increase the accuracy and precision of the Fe peaks, the BED, COO and BRO cores were run with a 45 µm Al filter. This eliminated any Al or Si peaks from the PIXE spectra. No filter is available to enhance Al and Si relative to Ca. No filters were used for PIGME analysis.

The beam diameter at the target was set to 2.0 mm and the sample stick stepped through the beam at 1.5 mm increments. This interval is equivalent to about 10 determinations per year of coral growth for the specimens used. At every tenth step the determination was repeated in order to test for replicability of the results and to detect damage to the target. Consistency of the results was determined from the replicate determinations.

The data are presented as peak areas only and absolute concentrations were not determined. Calcium was used as an internal standard for PIXE determinations, and results for each determination are given as ratios to the Ca peak area for that determination.

7.1.3 Results

7.1.3.1 Characteristics of the PIXE and PIGME spectra:

A typical PIXE spectrum for Rockingham Bay coral skeletal material is illustrated in Fig. 7.1.7a, showing the high background emissions by comparison with all elements except Ca and Sr. The paired peaks arise because of the different energy levels associated with K_α and K_β emissions. Although Al is apparent in the spectrum, this is due to the effect of the Al filter. Fig. 7.1.7b illustrates an atypical spectrum with a large Fe peak.

PIGME spectra for the same samples as in Fig. 7.1.7 are illustrated in Fig. 7.1.8. Note the similarity between the PIGME spectra, by comparison with the strongly contrasting PIXE spectra for the same samples.

7.1.3.2 Elemental evidence of variation in sediment concentrations:

As previously noted (7.1.2.1), the PIXE method is relatively insensitive to elements of atomic number ≤ 15 (Antilla *et al.*, 1981). In analyses undertaken on the KUB core, which is from the area of Rockingham Bay most likely to be affected by Tully River sediment plumes, no Al or Si was detected by PIXE. An Al or Si record in the Rockingham Bay corals is therefore reliant on the PIGME method, the Ge(Li) detector for which was not functioning at the time the KUB core was analysed. PIGME data were obtained for the COO and BRO cores, both from sites further offshore than the KUB core. Gamma energies (E_γ) appropriate to Al and Si determination, and possible interferences, are given in Table 7.1.5.

Element	E_γ (MeV)	Detection limit (ppm)*	Possible interferences
Al	0.844	20	Mg
	1.014	50	Ti, Mg
	1.369	n	Na, Mg
	1.779	n	Si, P
Si	1.273	30 000	
	1.384	n	
	1.779	n	Al, P

Table 7.1.5
E_γ, detection limit and interferences for Al and Si irradiated by protons (From Deconninck, Demortier and Bodart (1981) and Antilla, Hanninen and Raisanen (1981); * = beam energy and matrix not stated; n = detection limit not known).

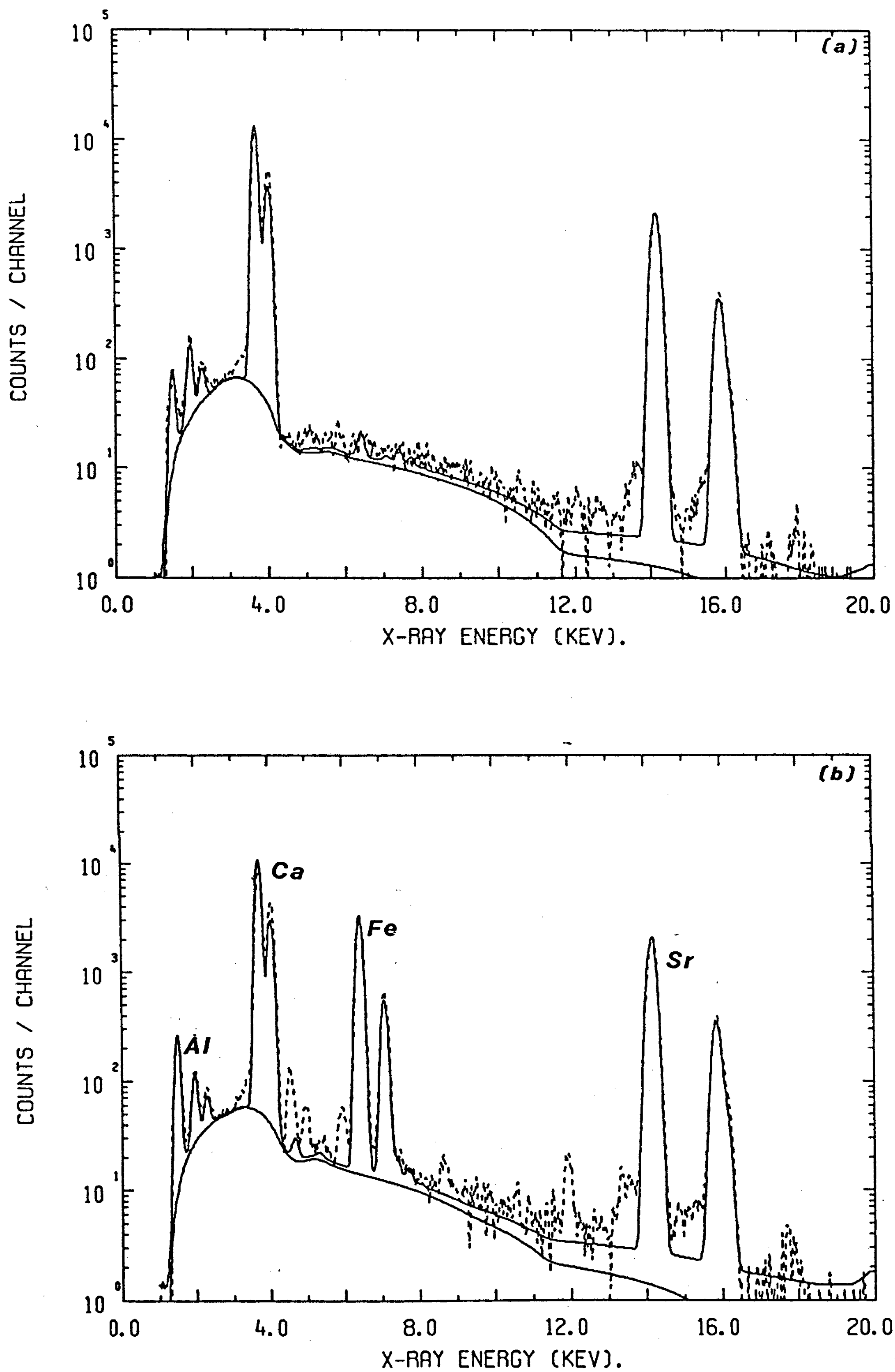


Fig 7.1.7
PIXE spectra for Rockingham Bay corals; (a) - determination with no detectable Fe; (b) - determination on adjacent skeleton with large Fe peak; beam energy = 2.7 MeV, 0.45 μm Al filter.

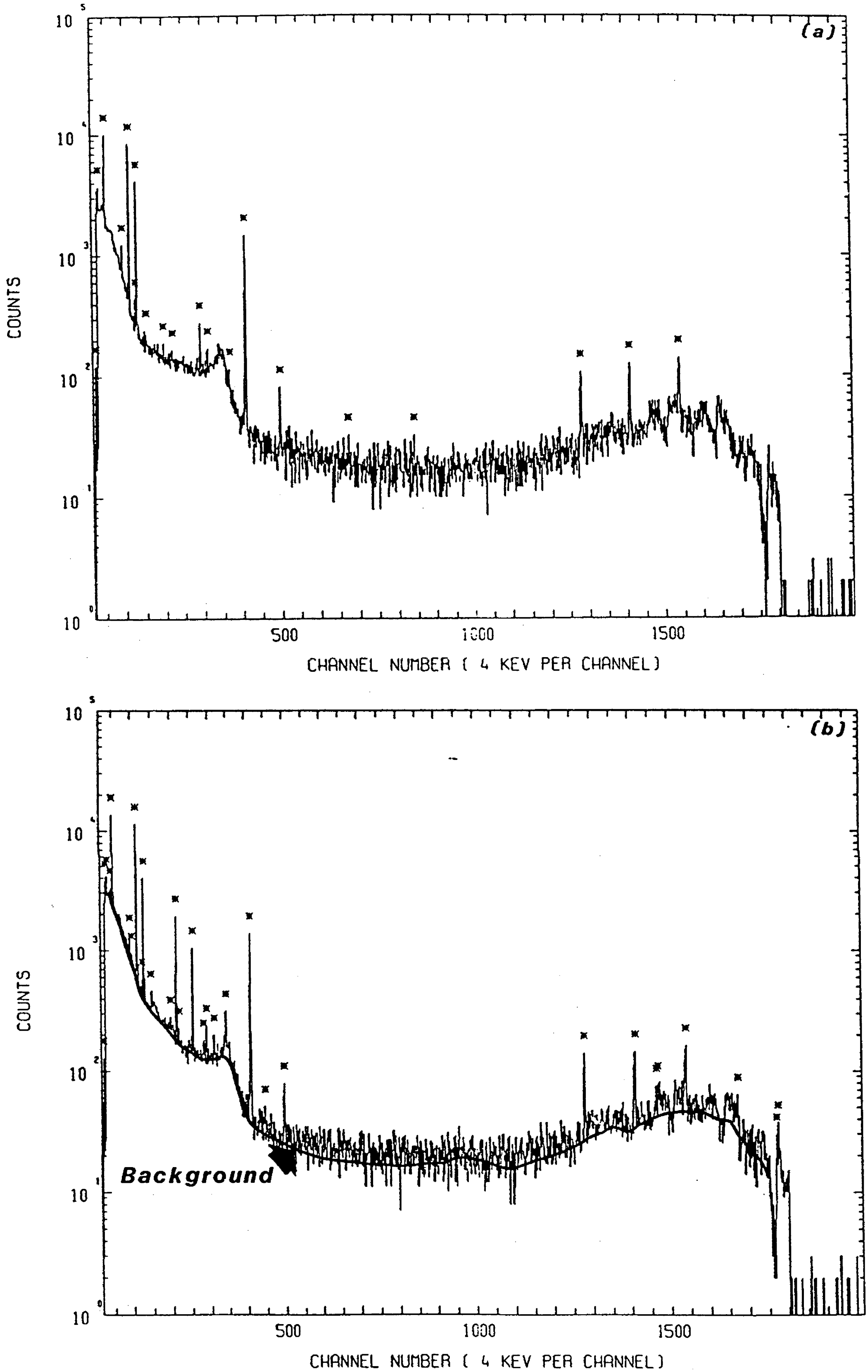


Fig 7.1.8
PIGME spectra for Rockingham Bay corals; (a) and (b) are the same determinations, respectively, as the PIXE spectra illustrated in Fig. 6.3.6; beam energy = 2.7 MeV.

PIGME Al time series: Given the likelihood of inclusions of non-terrigenous Si in the coral skeleton (Table 7.1.4), the 1.779 MeV gamma rays, which are emitted from Al, Si and P, are not a good measure of the Al inclusions. Although reactions with Mg yield low gamma emissions at E_γ for reactions with Al, Mg interference is a significant limitation because the concentration of Mg in coral skeleton (generally in the range 1 000 to 2 000 ppm (Cross and Cross, 1983; Swart, 1981)) is higher than that expected for Al. Similarly, Na is generally present in scleractinian coral skeletons at between 4 000 and 6 000 ppm (Swart, 1981). Furthermore, skeletal concentrations of Mg are related to growth rate and those of Na to the ambient concentration in the seawater (Swart, 1981). Consequently, these elements are likely to exhibit an inter- and intra-annual variability which confounds the interpretation of any Al signal. Given these factors and the relative γ-yields for Al illustrated in Fig. 7.1.6, the likely reliability ranking for Al E_γ is, in decreasing order, 0.844, 1.014 and 1.369 MeV.

Time series of the PIGME results for Al E_γ for the BRO core are shown in Fig. 7.1.9. These results indicate that there is little consistency between different E_γ of within the core, that trends are not consistent, and the highest peak area for one E_γ may occur for a determination in which no peak occurred at a different E_γ. By comparison, time series of the PIGME results for Al E_γ for the COO core (Fig. 7.1.10, 7.1.11 and 7.1.12) exhibit better correspondence between $E_\gamma = 0.844$ and $E_\gamma = 1.014$ MeV, but not between either of these E_γ and $E_\gamma = 1.369$ MeV. These associations are shown by the results of correlation analyses in Table 7.1.6 which presents a summary of the PIGME results for Al E_γ. These data show that:

(i) Peak areas are low in relation to standard errors, calculated using Eqn. 7.1.1. The average calculated error lies between 33 % and 53 % of the corresponding peak area for the six data sets. Fig. 7.1.13 shows that the calculated error never falls below 10 % and is below 20 % for only the highest peak areas ($E_\gamma = 0.844$). Precision of most of these determinations is therefore inadequate.

(ii) Errors determined by replicate analyses are similar to standard errors. Although the minimum errors determined by the replicate analyses are generally, but not always, acceptably low, the greatest errors are exceedingly high with differences by a factor of two between replicate determinations.

(iii) There is a poor correlation between peak areas at different E_γ. Although the relationship between $E_\gamma = 0.844$ MeV and $E_\gamma = 1.014$ MeV is significant in the BRO core, little of the variance is explained. Only in the relationship between $E_\gamma = 0.844$ MeV and $E_\gamma = 1.014$ MeV in the COO core is it both highly significant and explaining a large proportion of the variance.

	COO core			BRO core		
		E_γ (MeV)			E_γ (MeV)	
Parameter	0.844	1.014	1.369	0.844	1.014	1.369
No. of determinations*	368	368	368	220	220	220
No. of peaks recorded	198	100	121	167	121	133
% of determinations	53.8	27.2	32.9	75.9	55	60.4
Mean and Standard Deviation for the core						
$\bar{x}$ peak area	111.09	85.319	72.716	118.10	69.25	80.29
s.d.	64.34	40.20	28.40	41.93	26.75	32.60
minimum	21.33	27.65	31.53	33.57	29.24	15.02
maximum	317.88	197.65	185.16	267.51	179.46	269.76
Peak area standard error						
$\bar{x}$ % error**	42.38	47.299	52.6	33.12	51.31	47.28
Peak area replicate error						
(1st determination as standard)						
n (replicate analyses)	33	33	33	18	18	18
n (peaks for one obsv.)				18	10	12
n (peaks for both obsv.)	15	7	7	12	8	8
$\bar{x}$ % error	38.42	30.51	32.50	35.24	52.2	49.24
s.d.	49.53	18.43	16.54	40.9	62.88	56.40
minimum	2.212	1.84	9.75	3.9	0.02	11.65
maximum	192.02	54.3	54.42	156.50	199.50	185.18
Correlations (r^2)						
E_γ = 0.844 vs 1.014*	0.448***			0.195***		
(n)	88			115		
E_γ = 0.844 vs 1.369	0.065			0.012		
(n)	87			108		
E_γ = 1.014 vs 1.369		0.000			0.002	
(n)**		52			76	

Table 7.1.6
Summary data for PIGME determinations at E_γ = 0.844, 1.014 and 1.369 MeV on BRO and COO coral cores from Rockingham Bay (Data from * to ** exclusive of replicates; *** - significant $p \leq 0.01$).

(iv) The similarity of the peak area data sets (mean and standard deviation) for the COO and BRO cores, under conditions where the field data (Ch. 5) indicates much higher suspended sediment concentrations at Coomb Island than at sites further offshore, suggests that PIGME results at Al E_γ do not provide a good record of the inclusion of terrigenous detritus in coral skeleton. There is no significant difference between the means of these data sets for any E_γ (Kolmogorov-Smirnov test).

(v) Even for the highest peak areas in the COO core at E_γ = 0.844, 1.014 and 1.369 the peak areas are also low in relation to the background area (Table 7.1.7). In most cases the peak area is only c. 10 - 20 % of the background area.

E_γ	Peak area	Background area	Peak area as % of background
0.844	317.88	795.49	40.0
1.014	197.65	668.59	29.5
1.369	185.16	1 296.85	14.3

Table 7.1.7
Peak area in relation to background for the highest peak areas (COO core) at E_γ = 0.844, 1.014 and 1.369.

Time series of the PIGME results in relation to the Tully River sediment yield estimates (Fig. 4.3.2) are shown in Figs. 7.1.10, 7.1.11 and 7.1.12 for E_γ = 0.844, 1.014 and 1.369 MeV, respectively, for the COO core. This relationship for E_γ = 0.844 MeV in the BRO core is shown in Fig. 7.1.14. These results indicate that there is no consistency between the PIGME results and the sediment yield estimates in the case of the BRO core. In the COO core the results are, at first inspection, more encouraging. The year of highest estimated sediment yield (1967) coincides with a region of high gamma yields from the coral skeleton at E_γ = 0.844, 1.014 and 1.369 MeV. However, closer examination reveals that the peak area maxima occur on three different runs for the three emission energies. Furthermore, the high Al gamma emission region of the coral skeleton extends across several years, including 1966, ranked with 1926 as the year of lowest sediment yield. The highest gamma emissions at E_γ = 0.844 and 1.014 MeV occur during the years 1958 to 1960, at which time estimated sediment yields are not high. Neither is there any notably high fluorescence peak during this period, so river plume effects concentrated in the Coomb Island area cannot be invoked as an explanation. However, examination of the coral core under UV light shows dark stains in this part of the core. High gamma yields in the period 1947 to 1951 are also associated with dark stained core. Examination of these stained areas, and similar sections of other cores and slices through whole colonies, indicates that these stains are consistent with contamination introduced into the coral skeleton after calcification. This possibility is further examined below.

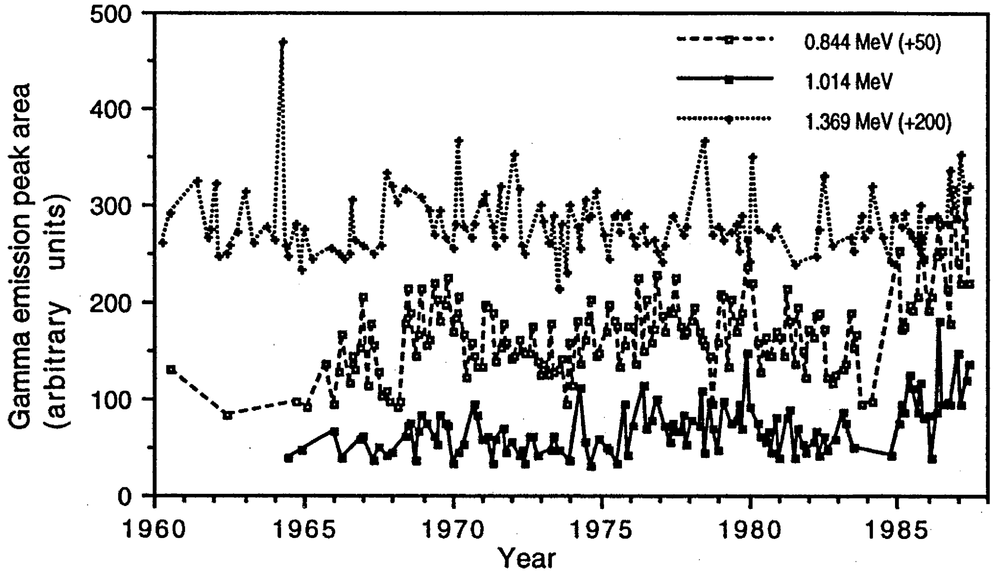


Fig. 7.1.9
Time series of PIGME peak areas for E_γ = 0.844, 1.014 and 1.369 MeV (BRO core)

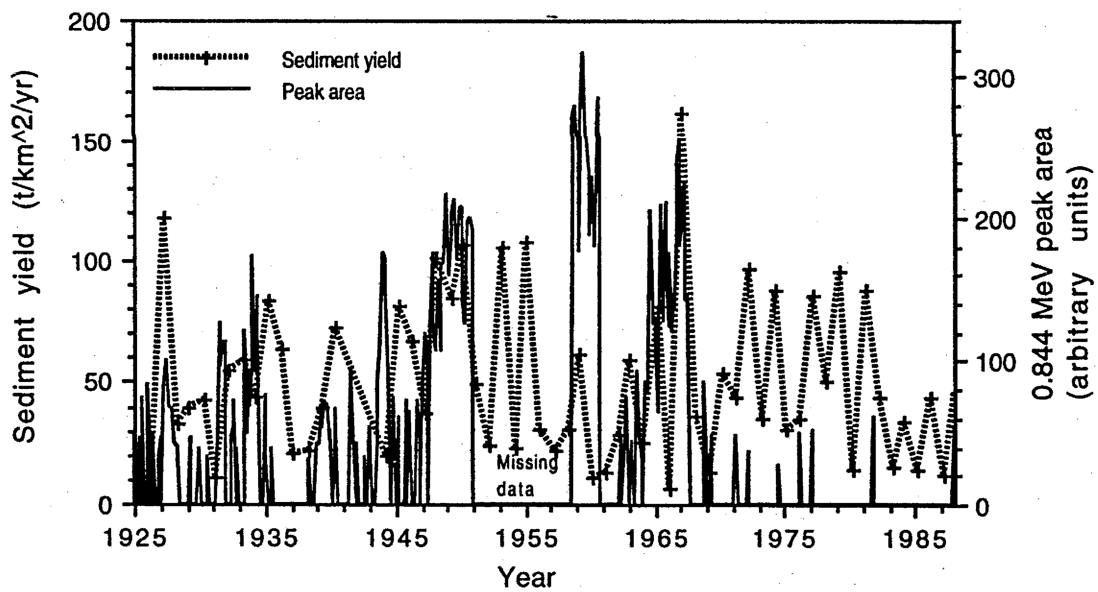


Fig. 7.1.10
Time series of Tully River sediment yield and E_γ = 0.844 MeV peak areas (COO core)

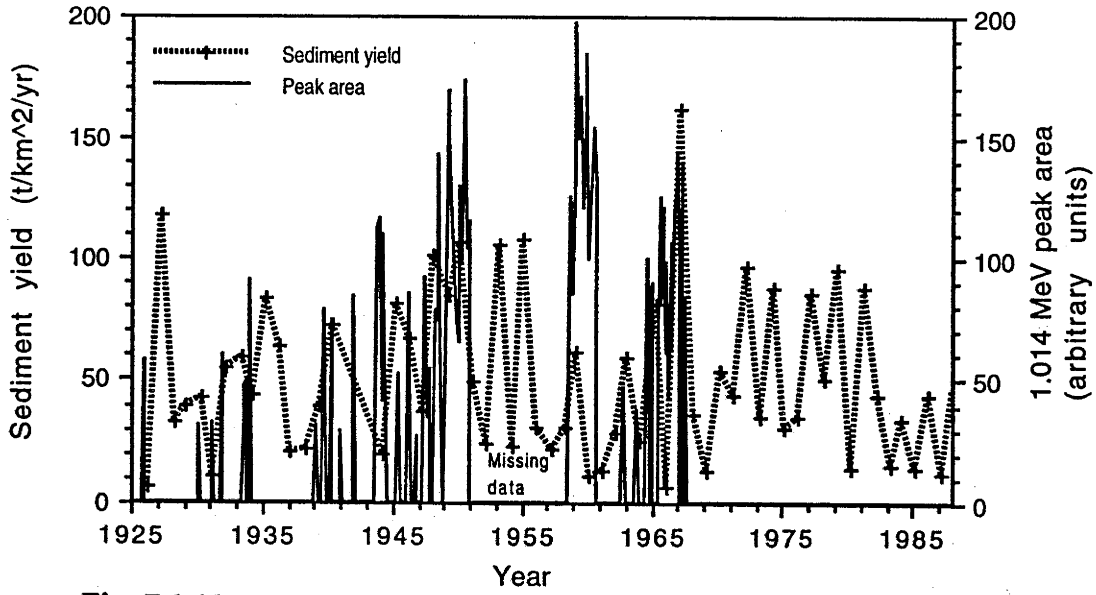


Fig. 7.1.11
Time series of Tully River sediment yield and E_γ = 1.014 MeV peak areas (COO core)

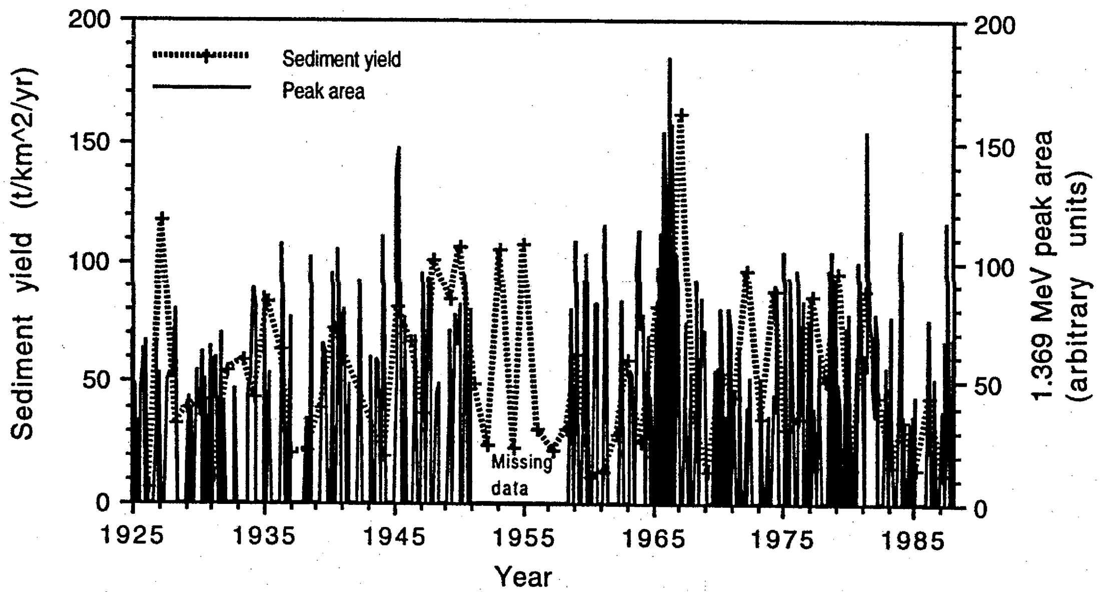


Fig. 7.1.12
Time series of Tully River sediment yield and E_γ = 1.369 MeV peak areas (COO core)

These results lead to the following conclusions:

(i) Gamma yields consistent with Al (E_γ = 0.844, 1.014 and 1.369 MeV) are too low, and the associated errors too high, for adequately precise analysis.

(ii) Inability to adequately discriminate Al gamma emissions from those of Mg and Na, both present in significant concentrations in coral skeleton, render interpretation of the already inadequate emissions difficult. No software for the separation of elements with gamma emissions at the same energies was available at the time of these analyses.

(iii) Contamination in the coral skeleton, discussed further below, is a limitation which cannot be resolved while using surface analysis techniques on intact coral skeleton.

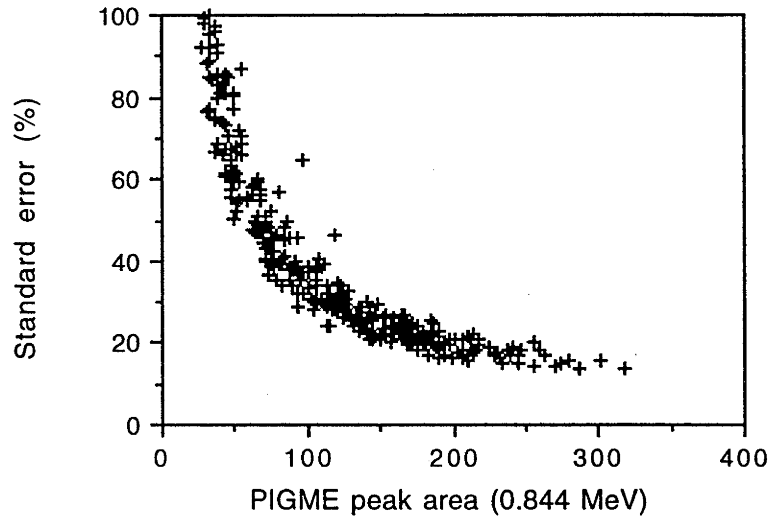


Fig. 7.1.13
Relationship between peak area and standard error (%) for E_{γ} = 0.844 MeV (COO core).

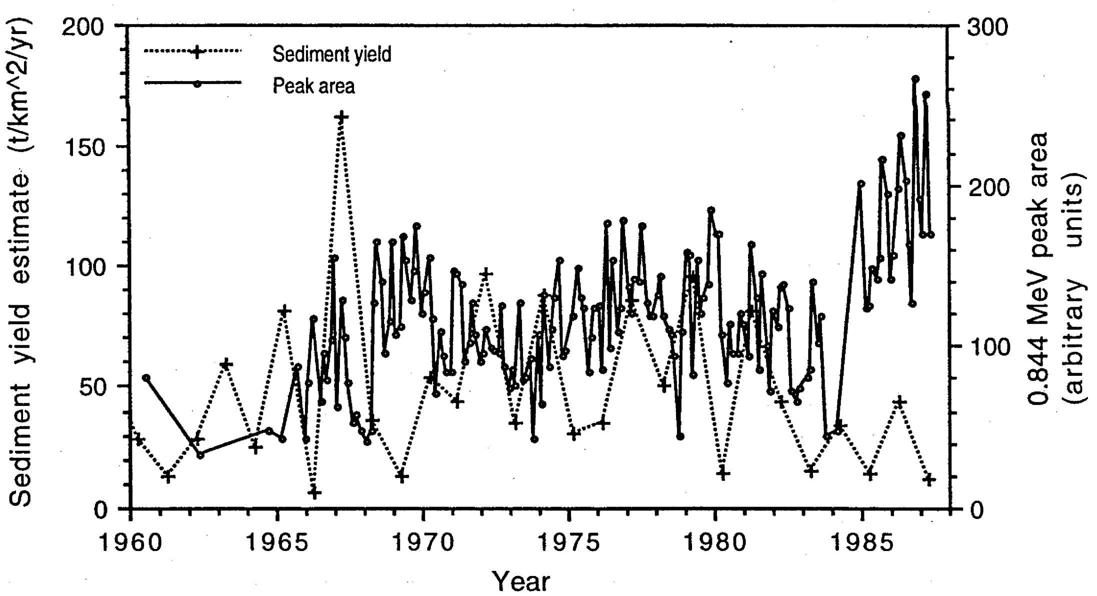


Fig. 7.1.14
Time series of the Tully River sediment yield estimate and the 0.844 MeV PIGME results for the BRO core.

PIGME Si time series: The limitations of Si as a recorder of terrigenous inputs have been discussed previously. However, given the limitations of the PIGME record of Al concentrations, the Si data acquired from the PIGME analyses of the COO and BRO cores is evaluated. Table 7.1.8 shows that the number of interpreted Si peaks is low, the associated errors are higher than for Al E_γ, and unacceptably high for almost all determinations (Fig. 7.1.15).

Furthermore, as illustrated in Figs. 7.1.16 and 7.1.17, for the COO and BRO cores respectively, there is no consistency between the different E_γ within a core, between cores or between gamma yields and the sediment yield estimates. The presence of five 1.273 MeV peaks in the COO core data is inconsistent with the reported detection limit of 30 000 ppm (Table 7.1.), given that expected concentrations in coral skeleton are three to four orders of magnitude lower. Neither are they consistent with peaks in sediment yield or at other Si emission energies.

The PIGME record of skeletal Si concentrations is of no practical value and includes several probably spurious results (Fig. 7.1.16).

	COO core			BRO core	
		E_γ (MeV)		E_γ (MeV)	
Parameter	1.273	1.384	1.779	1.384	1.779
No. of determinations	368	368	368	220	220
No. of peaks recorded	5	21	8	20	3
% of determinations	1.4	5.7	2.2	10	1.4
Mean and Standard Deviation for the core					
$\bar{x}$ peak area	48.86	99.25	17.97	100.83	18.82
s.d.	13.82	80.03	3.37	46.54	7.79
minimum	31.02	35.89	13.75	37.27	11.60
maximum	67.73	333.48	22.81	230.51	27.08
Peak area standard error					
$\bar{x}$ % error	71.86	46.66	73.55	38.89	78.11
s.d.	17.12	20.77	9.47	15.20	18.44
minimum	46.14	14.7	63.55	19.28	60.04
maximum	92.58	89.51	84.54	68.42	96.90

Table 7.1.8
Summary data for PIGME determinations at E_γ = 1.273, 1.384 and 1.779 MeV on BRO and COO coral cores from Rockingham Bay (Data are exclusive of replicates; None of these correlations is significant).

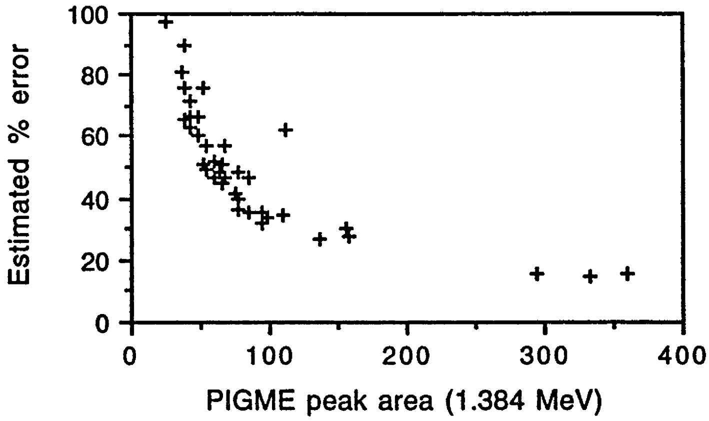


Fig. 7.1.15
Relationship between peak area and estimated % error for E_γ = 1.384 MeV (COO core).

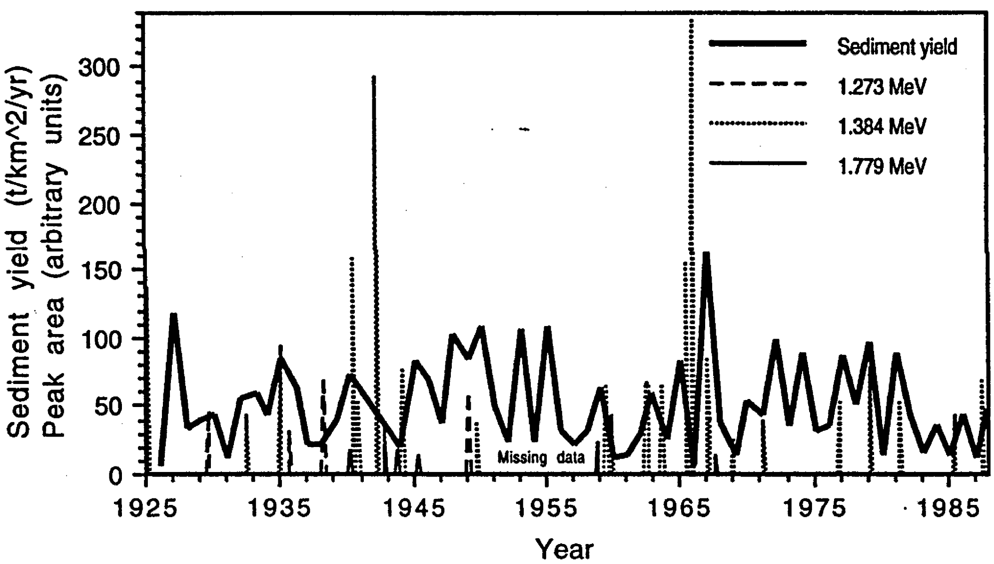


Fig. 7.1.16
Time series of Tully River sediment yield and Si E_γ peak areas (COO core)

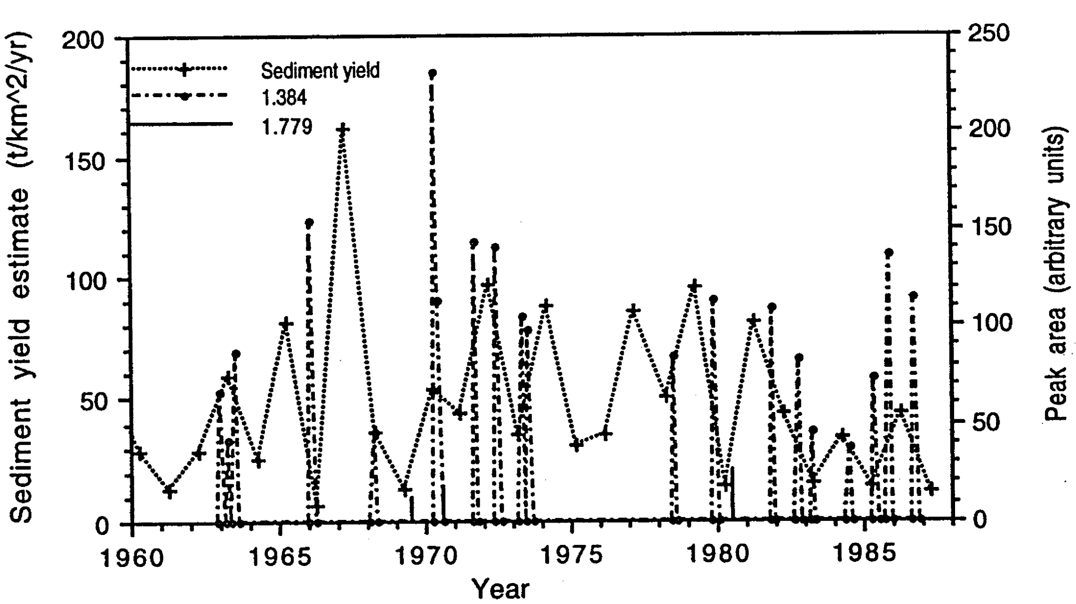


Fig. 7.1.17
Time series of Tully River sediment yield and Si Eγ peak areas (BRO core)

PIXE Fe time series: The third element potentially diagnostic of terrigenous inclusions in the coral skeleton is iron, best detected using PIXE analysis. Given that no Al or Si was detected in the PIXE analysis of the KUB core, the mylar filter was replaced by 45 µm of aluminium in order to suppress the Ca peak and enhance the relative magnitudes of the Fe and Sr peaks. Analyses of the BED, COO and BRO cores were undertaken with this experimental configuration.

As previously noted, the BED core, and slices from other, smaller coral heads obtained from its vicinity, had a hiatus in growth interpreted (by cross-matching fluorescent banding patterns with other cores) as having occurred between 1981 and 1982. As a result of uncertainty in this interpretation, the BED core is of limited value in determining time series of sediment inclusions. It is of interest in other respects, and results from its analysis will be discussed below.

Fe determinations are analysed with respect to Ca peak areas, so a brief discussion of the characteristics of the Ca determinations is appropriate. In the cores analysed, Ca peak areas exhibit a cyclicity which appears to have an approximately annual period. The amplitude of this cyclicity is about 1.5 to 2.5 times the calculated average difference between replicate determinations. It is possible that this cyclicity is a response to variation in skeletal density, as has been suggested for other surface analysis determinations on coral skeleton such as electron spin resonance (Ikeda *et al.*, 1992). Lagged autocorrelation of Ca determinations for each of the cores does not indicate an annual period, as expected for a signal responding to density variations. However, skeletal density, as determined by gamma densitometry, does not either (Fig. 7.1.18) probably because of the complexity of density banding (Barnes and Devereaux, 1988; Lough and Barnes, 1990a, b), particularly in nearshore corals where "stress bands" may occur, and variations in the annual growth increment. Trends in Ca peak areas are not consistent between cores, although neither are they for skeletal density.

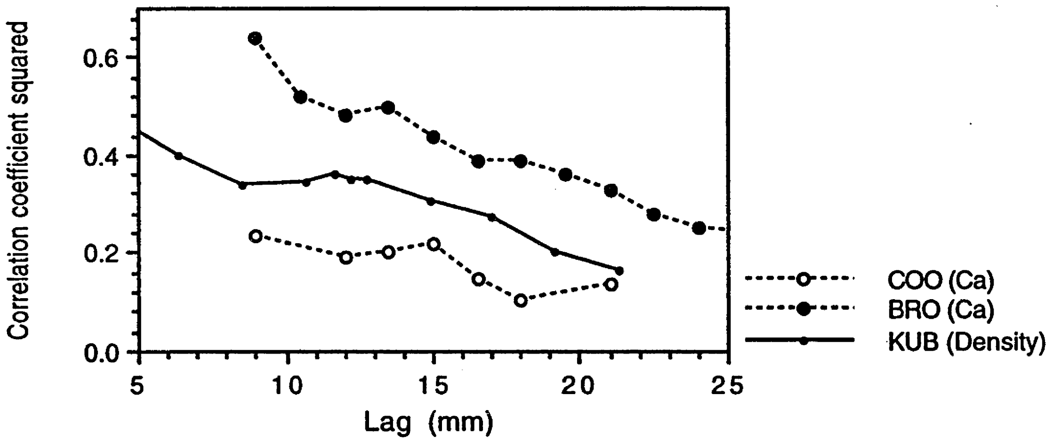


Fig. 7.1.18
Lagged autocorrelation of calcium peak area and of skeletal density.

Fe:Ca ratios are strongly correlated with Fe peak areas ($r^2 = 0.472$, COO; $r^2 = 0.753$, BRO) and poorly correlated with Ca peak areas ($r^2 = 0.053$, COO; $r^2 = 0.047$, BRO) indicating that variability in Fe, rather than in Ca, is the major factor determining the Fe:Ca ratio.

Time series of Fe:Ca determinations in the COO and BRO cores are presented in Fig. 7.1.19 and 7.1.20, respectively. These data show that the Fe:Ca values are not correlated with the sediment yield time series in either case. Neither are they consistent with the PIGME results.

Although it is clear that no continuous record of suspended sediment concentrations is available from the technique used, it is of interest to examine the record of episodic, low-frequency, high-magnitude events as it is these events which are of greatest significance in erosion processes.

Fig. 7.1.19 and 7.1.20 clearly show a number of spikes which indicate relatively high Fe concentrations in the coral skeleton. It is important to note that, for the period of time for which data are available from both the COO and BRO cores, there is little agreement between the two.

Higher Fe:Ca ratios in the COO core are expected, given that this core site is closer to shore and, therefore, subject to increased sedimentation by both fluvial sediment plumes and by bottom sediment resuspension. There is no evidence that this is the case. The mean Fe:Ca for the COO core (1.92×10^{-3})

is < 3 % greater than the BRO core mean (1.86 x 10^{-3}). There is no significant difference between these two data sets (Kolmogorov-Smirnov test).

There are three likely sources of the low amplitude variability evident throughout the series:- i. random error, ii. seasonal variation in skeletal density, and iii. seasonal variation in sediment inclusions. Of these, random error is considered to be the major source as a result of the very low signal:noise ratio. Consequently, the Fe:Ca time series generated by the PIXE method is not a viable technique for monitoring continuous variation in sediment concentrations in nearshore waters.

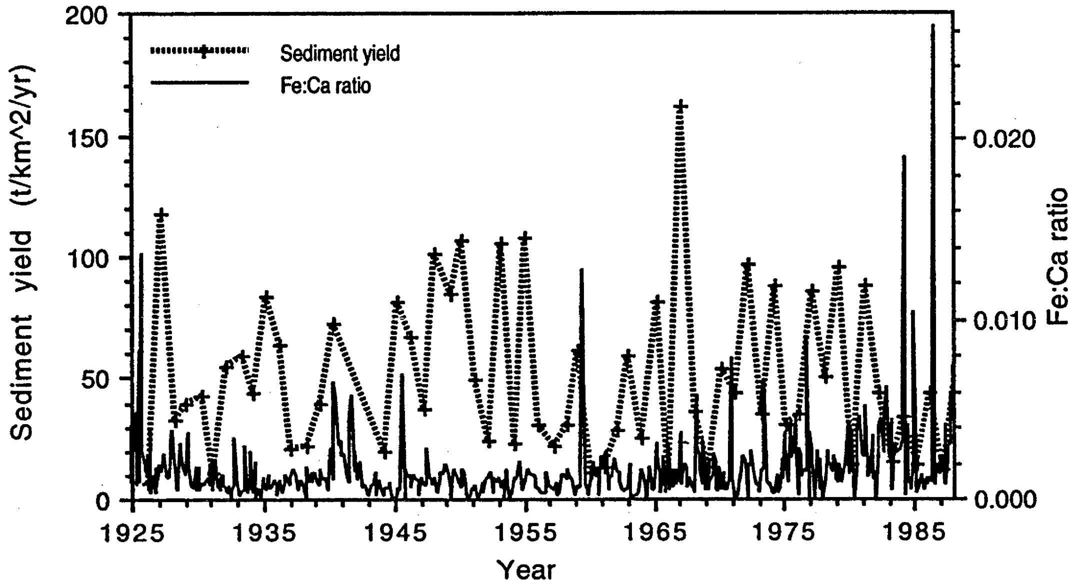


Fig. 7.1.19
Time series of Tully River sediment yield and Fe:Ca ratios in the COO core.

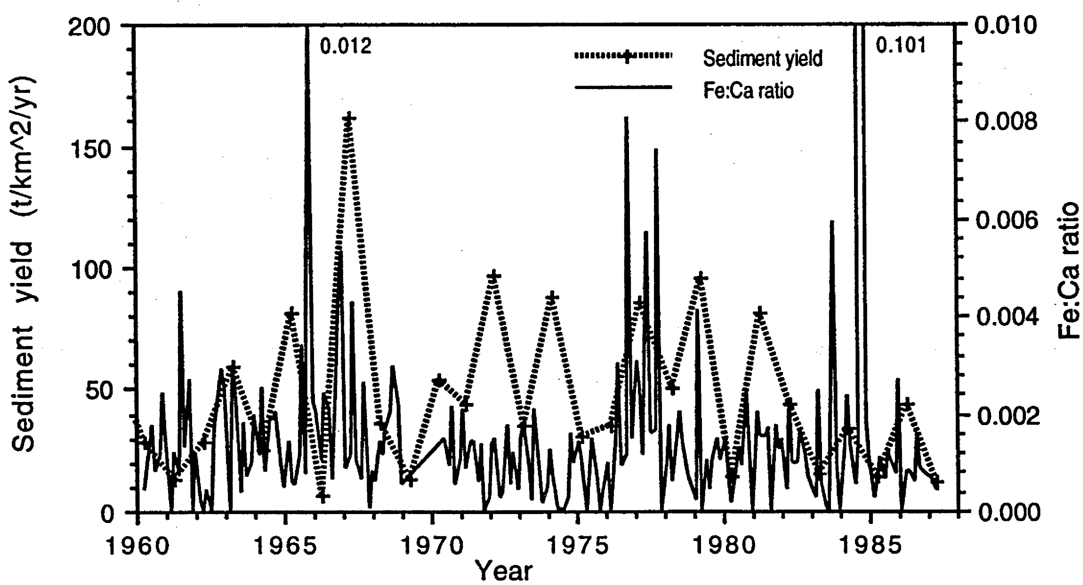


Fig. 7.1.20
Time series of Tully River sediment yield and Fe:Ca ratios in the BRO core.

7.1.3.3 *Limitations of the PIXE/PIGME analyses:*

There are numerous factors which may contribute to errors and uncertainities in the determination and interpretation of elemental concentrations in coral skeletal material using the PIXE/PIGME method. These include the replicability of determinations, damage to the target, instrument drift, variability in the skeletal morphology, low concentrations of the target elements, inconsistent proton beam conditions, and unexplained discontinuities in the data acquired. Each of these factors is discussed in turn below.

(i) Replicability of determinations: Summary statistics for comparisons of the replicate PIXE determinations for cores KUB, BED, COO, and BRO are given in Table 7.1.9. These statistics are calculated on the raw peak area counts for Ca determinations, and on the peak area ratios to Ca for Sr and Fe determinations. The absolute % difference is calculated as the percentage by which the difference between replicate determinations exceeds the smaller value of the two determinations. For the four cores analysed the mean of the absolute differences between the replicate Ca determinations is 4.4, 2.5, 1.9 and 7.9 % for the KUB, BED, COO, and BRO cores respectively and for Sr determinations is 4.7, 1.7, 8.0 and 5.3 %. Median errors are always lower than the means.

These results indicate that a PIXE peak area determination error of less than 10 % is the norm for Ca and Sr at the concentrations at which they occur in the coral skeleton. These errors are low and are not dissimilar to differences reported in the literature (Borderie *et al.*, 1980).

Examination of the maximum values given in Table 7.1.9 shows that the errors may be much greater, up to 93 % for Sr in the COO core. The means of the absolute differences between the replicate Fe determinations are 24.2, 187.9 and 36.2 % for the BED, COO, and BRO cores respectively. These errors are sufficiently large to require extreme caution in interpretation of the Fe determinations. The same conclusion is reached with respect to the PIGME results, given the errors associated with (E_γ) for Al and Si presented in Tables 7.1.6 and 7.1.8, respectively.

CORE	KUB		BED			COO			BRO		
Element	Ca	Sr	Ca	Sr	Fe	Ca	Sr	Fe	Ca	Sr	Fe
Absolute % difference	4.4	4.7	2.5	1.7	24.2	1.9	8.0	187.9	7.9	5.3	36.2
Median	4.1	3.0	1.8	0.8	11.6	1.3	3.7	74.1	4.8	3.6	15.0
Std. Dev.	5.1	4.4	1.9	1.7	36.0	2.8	14.9	343.4	10.2	5.3	39.5
Min.	1.49	0.72	0.44	0.15	0.39	0.015	0.059	1.12	0.058	0.37	2.24
Max.	8.2	13.8	8.7	5.8	156.9	13.9	93.2	1 733	36.8	19.2	132.6
% of determinations with peak area of 1st determination > that for 2nd determination											
	43	86	32	74	47	54	52	52	73	40	53
n (pairs)	7	7	19	19	19	48	48	43	15	15	15
Difference statistics for Fe count > Fe M.D.L. only.											
Absolute % difference					20.6			59.3			41.3
Std. Dev.					43.3			65.3			61.0
n					12			15			4

Table 7.1.9
Descriptive statistics of the differences between replicate PIXE determinations for the KUB, BED, COO and BRO cores.

(ii) Target damage: The effect of target damage on the coral sections used in this analysis was investigated by comparing the results of the first and second determinations of replicate analyses. Target damage would be expected to appear as a consistent difference between the first and second peak area determinations for any element. Fe and Sr are both heavier than Ca so the direction of drift with respect to Ca should be the same for both of these elements. The generally random nature of the data given in the row "% of determinations with 1st determination > 2nd determination" in Table 7.1.9 suggests that this is not the case. Furthermore, in the case of the COO core, for example, there are 48 replicate analyses of which 25 first determinations are greater than the replicate. Of these 25, however, there are only 9 cases where the first determination is greater than the replicate for both Sr and Fe. Therefore, it is concluded that there is no significant effect on the X-ray emissions due to target damage at the settings used in these analyses. Ca and Fe are reported to be stable under sequential irradiations (Alexander *et al.*, 1974; Campbell *et al.*, 1975). These results suggest that Sr is also.

Ion beam methods are considered non-destructive. However, as thin (1.7 mm) coral slices are stepped through the proton beam they are cut in half.

The separation occurs at a distance of c. 10 - 50 mm behind the spot being analysed so there is no effect on the X-ray spectra. It is caused by stress in the slice, not by random movement of the proton beam. This problem, which does not occur with thick (7 mm) slices, limits the analyses which can be undertaken subsequently.

(iii) Drift: The replicate determinations give no indication of whether drift occurred during a series of analyses. Given that the trace element determinations are undertaken with reference to Ca as an internal standard, drift should only be a consideration if X-ray emissions for the various elements are not equally affected by a given change in running conditions. This question is further discussed in (vii) below.

(iv) Variability of skeletal morphology: In the case of a smooth, high density surface of homogeneous composition, proton penetration is consistent within the target area for a given determination and between target areas for sequential determinations. In the case of coral skeleton, however, the surface is porous, pore alignment varies along the core and both porosity and density vary. Consequently, proton beam penetration in coral skeleton is variable and so also is the thickness and density of $CaCO_3$ through which emitted X-rays and γ-rays must pass in order to reach the detector. Because low energy X-rays (from low atomic number elements) are attenuated to a greater degree than those of high energy, in coral of high porosity or density a relatively high proportion of high energy X-rays (in this case Fe and Sr) would reach the detector. As a result, Ca peak areas and Fe:Ca and Sr:Ca ratios are likely to vary slightly in response to seasonal and secular variation in porosity and density. This problem is of much less importance for PIGME analyses because of the much higher energies of γ-rays.

An additional factor is the orientation of the coral pores in relation to the incident proton beam and to the detector solid angle. This is, in part, controlled by the angle at which the growth axis of each corallite intersects the surface of the coral slice.

(v) Low concentrations of target elements: Although the preliminary analyses indicated the presence of the relevant elements at detectable concentrations, these concentrations were only marginally greater than the expected analytical limits. For example, analysis of the results of numerous Fe measurements shows how few are capable of providing meaningful results. Estimates of the error of the peak areas calculated are obtained from Eqn. 7.1.1. Fig. 7.1.21 shows that, for Fe peak areas < 50, the calculated error is

generally $\geq$ 50 %. Similarly, the M.D.L. (Eqn. 7.1.2) for Fe peak area = 50 is about 50. Fig. 7.1.22 shows that, of the 631 PIXE determinations on the COO core, 83 % of Fe peak areas lie in the range 0 - 50. Errors in relation to peak area for 0.844 and 1.384 MeV γ-rays were shown in Figs. 7.1.13 and 7.1.15, respectively.

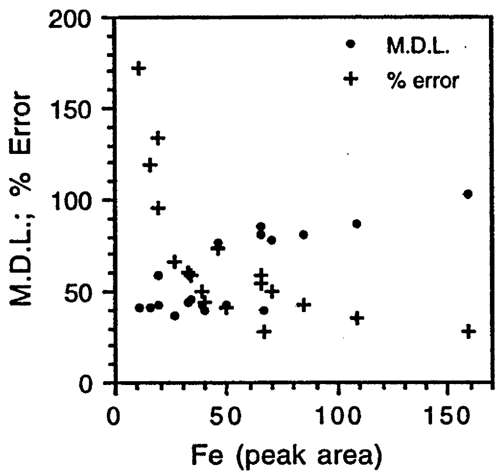


Fig. 7.1.21
Relationship between Fe peak area and the corresponding % error and minimum detectable limit, calculated from Eqns. 7.1.1 and 7.1.2, respectively.

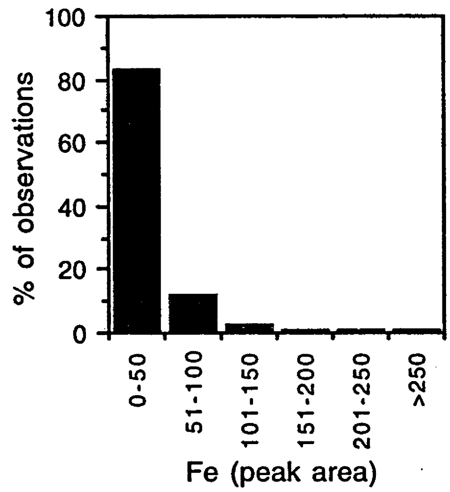


Fig. 7.1.22
% of Fe peak area observations occurring in six peak area classes (n = 631; COO core).

<u>*(vi) Inconsistent proton beam conditions and other technical problems:*</u>
Throughout the running of the PIXE/PIGME analyses, fluctuations in the condition of the proton beam and a variety of other technical problems were a cause of concern. Problems encountered included differences of opinion amongst AINSE and ANSTO staff as to whether the Ge(Li) (PIGME) detector was serviceable (and on many other technical questions). Filling the liquid nitrogen chambers used for cooling the detectors seemed to influence running conditions as did electrical activity due to thunderstorms. Substantial variations in the target current were common between and during runs, and problems with variation in beam aperture and steering occurred. Significant differences in results occurred when PIXE/PIGME determinations were repeated on a given length of coral skeleton after an accelerator malfunction and shutdown. Consequently, a decision to run continuously was made. Debate as to whether the automated stepping of the sample-stick was reliable (the weight of opinion indicating that it was not) required continuous manual operation over many days. I am indebted to Dr D.S. Newman, then of AINSE, for his assistance, patience and persistence in

this task. In spite of this attempt to maintain constant running conditions, frequent adjustment of accelerator settings was required and accelerator shutdowns still occurred, from known (eg. lightning strike in the vicinity) and unknown (possibly mains voltage surges) causes.

(vii) Discontinuities in the time series results: Most of the abovementioned limitations and problems have similarities to limitations of other analytical methods or were consistent with the expected X-ray and γ-ray behaviour. However, there are several marked discontinuities in the time series results.

There are several possible explanations for these discontinuities:

1. Analysis of the spectra was carried out in blocks, generally of about 50 spectra. Discontinuities could result from errors in specification of the PIXAN commands for different blocks of spectra. However, there are discontinuities that do not occur between blocks of analyses and, when spectra either side of a discontinuity were re-analysed in a single block the results were unchanged.

2. Inconsistencies in the ion beam condition were experienced during a number of runs either side of a discontinuity in the BED core in 1982. Marked differences in the target current occurred between the two runs (85 and 86) immediately prior to this discontinuity. These two runs were replicate determinations on the same spot. Table 7.1.10 shows that the target currents, running times and peak areas differed by a factor of two for these replicate runs. However, the element ratios were consistent, suggesting that fluctuations in the ion beam were not the cause of this discontinuity.

Parameter	Result		
	Run 85	Run 86	Run 87
	Replicates		Discontinuity
$\bar{x}$ Target current (nA)	140	60	140
Running time (min)	3:28	7:31	3:16
Ca peak area	201 732	420 777	110 810
Sr peak area	32 716	68 619	28 184
Fe peak area	3 283	6 941	1 865
Sr:Ca	0.162	0.163	0.254
Fe:Ca	0.0163	0.0165	0.0168

Table 7.1.10
Characteristics of PIXE determinations before and after the 1982 discontinuity in the BED core.

3. The problem of differing results before and after an accelerator shutdown has already been mentioned. Discontinuities occur at times when there was no accelerator shutdown.

4. Problems such as electrical shorts between the sample stick and the Faraday cup often required opening of the target chamber and removal of the sample stick, which requires withdrawal of the Si(Li) detector. Failure to reset this detector to the correct position could induce discontinuities in results. However, the Ge (Li) detector is fixed, so that discontinuity in the PIGME data would indicate a cause other than incorrect Si(Li) detector position. Discontinuities in both PIXE and PIGME measurements occur in cores for which both data types are available, indicating that Si(Li) position is not the problem.

5. The geometry of the target chamber and sample stick is such that, regardless of the sample thickness, the angles between the beam, the target and the detectors are constant so both PIXE and PIGME spectra should be independent of sample thickness. Furthermore, the expected beam penetration (<50 μm) is only 3 % of the thickness of the thin slices, although, in practice, burn marks to depths of 200 - 800 μm indicate that beam penetration in the porous coral skeleton is much greater than expected. Discontinuities in the COO core appear to be associated with changes in the slice thickness. However, discontinuities in the BED core occur on slices of consistent 7 mm thickness.

The foregoing discussion shows that it is unclear what the cause of these discontinuities in the data is, or if different causes or combinations of causes apply at different times or if the cause/s are other than those canvassed above. As a result of these uncertainties the data were treated as follows. The relationship of Fe to Ca appears relatively unaffected. The discontinuity at 1968 in the COO core was adjusted by re-scaling the Fe:Ca ratios for the period 1968-1988 by the difference between the means of the fifty runs either side of the discontinuity. No other re-scaling of Fe:Ca ratios was necessary.

7.1.4 Discussion of the PIXE/PIGME results:

The "spikes" in the Al E_γ, Si E_γ and Fe:Ca ratios in the COO and BRO cores could arise from any of the following sources:-

i. Suspended sediment of fluvial origin.
ii. Suspended sediment generated by wave action.
iii. Contamination via boring by endolithic fauna.
iv. Analytical error.

(i) Suspended sediment of fluvial origin: The temporal pattern of Fe:Ca ratios is not consistent with the temporal sequence of major rainfall and stream flow events. The 1970s was a period of high annual discharge totals and frequent flooding, yet there are few Fe:Ca spikes by comparison with the 1980s, during which there were fewer floods. The major floods of 1979 and 1981 are not represented. The 1967 flood may be represented in the BRO core, but is not in the COO core.

Similarly, patterns in the "spikes" in the Al E_γ, Si E_γ and Fe:Ca ratios are not consistent with the inferred sediment yield response to land use change in the Tully River catchment (Fig. 4.3.2) as shown by the results for each of these elements presented in Chapter 7.1.2. It is, therefore, difficult to attribute any part of the temporal pattern in Al E_γ, Si E_γ or Fe:Ca ratios in the coral cores to variation in fluvial inputs.

(ii) Suspended sediment generated by wave action: Comparison of the time series of Al E_γ, Si E_γ and Fe:Ca ratios with the time series of strong wind occurrence on the north Queensland coast (Fig. 2.2.6) shows that there is no evidence that the patterns of Al E_γ, Si E_γ or Fe:Ca ratios in the coral cores are determined or influenced by bottom sediment resuspension. However, the period for which wind data is available is short for most stations and, as Fig. 2.2.6 shows, there is little consistency between the wind recording stations. The temporal pattern in Al E_γ, Si E_γ or Fe:Ca ratios in the coral cores apparently cannot be attributed to resuspended sediments.

(iii) Contamination via boring by endolithic fauna: Contamination of the coral skeleton by infiltration from the holes drilled by boring organisms is a potential problem for any analytical method applied to these materials, and is not specific to the PIXE/PIGME method. For example, Scoffin *et al.* (1989) observed that the presence of endoliths, such as sponges, bivalves and worms, locally reduced the intensity of skeletal fluorescence and obscured the banding pattern. Visual examination of coral skeleton in the vicinity of such bore holes (best done with long-wave UV backlighting) shows that infusion of fine muds occurs radially from the bore hole. However, this infusion does not occur evenly, but preferentially by lateral movement parallel to the growth bands. Consequently, spurious bands of apparently high clay concentration could be formed after calcification has occurred. Lateral movement is more important than vertical movement in this process, because of the unusually porous skeleton of *Porites* spp. corals in which the thecae do not completely isolate calixes from each other (Barnes and Lough, 1992) and because of the presence of sheet dissepiments in the

Porites skeleton (Wells, 1969; Barnes and Lough, 1989) which are likely to inhibit vertical infiltration (D. Barnes, 1987; pers. comm.). Nevertheless, the distribution of sediment inclusions (as Fe:Ca ratios) about the 1981 growth hiatus in the BED core (Fig. 7.1.23), with high Fe:Ca ratios both above and below this break in growth, are interpreted as a consequence of vertical infusion. Although the high concentrations prior to cessation of growth could have occurred during calcification, and could have been the cause of coral death, this seems unlikely. Neither bottom sediment resuspension nor sediment yield during 1980 is inferred to have been particularly high. Coral death is more likely to have been related to the 1981 flood. Infusion upward after the renewed coral growth may have occurred through the intermittent gap which lies between the dead surface and the new growth.

The BED core, from the site closest to the Tully River mouth, is the one most likely to have a high level of sediment inclusions. The absence from the BED core of the very high Fe:Ca peaks which are evident in the COO core during the mid-1980s (Fig. 7.1.19) is evidence that those peaks in the COO core may be spurious, either due to analytical error or to contamination through boring by endolithic fauna. Comparison of the Fe:Ca peak areas in the BED core, where contamination is clearly evident adjacent to the break in growth, with those in the COO core during the 1980s where there is little evidence of contamination, suggests that analytical error is the most likely explanation of the very high Fe:Ca peaks in the COO core during the 1980s.

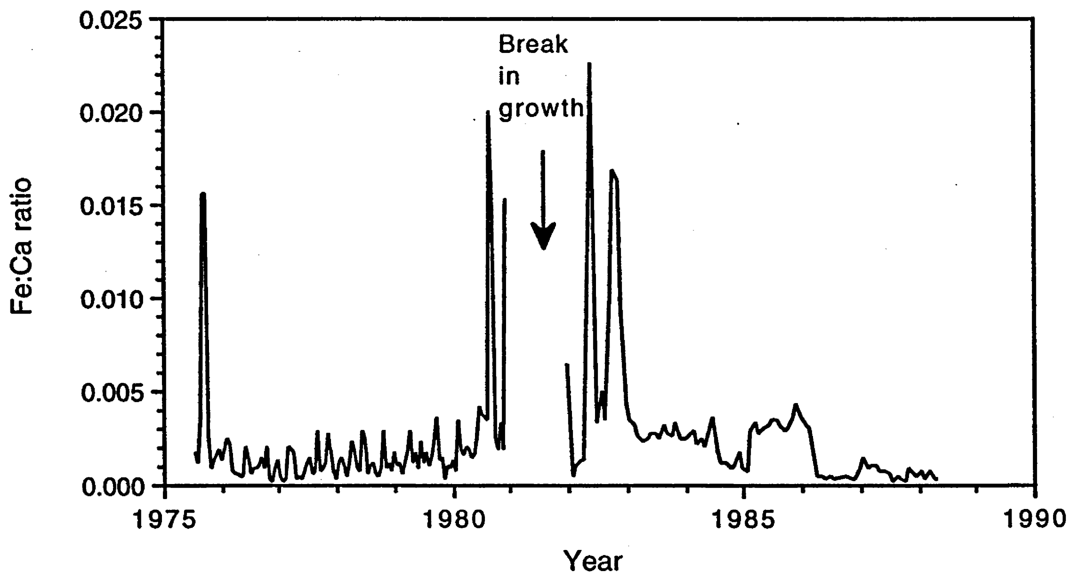


Fig. 7.1.23
Time series of Fe:Ca peak area ratio for the BED core, showing high Fe concentrations in the coral skeleton both above and below the break in growth.

Detailed examination of the COO core shows that patchy darkening of the skeleton (consistent with contamination) is evident in several areas. This is illustrated in Fig. 7.1.24 using a black and white exposure of coral skeleton under UV light. This interpretation is much clearer when viewing the skeleton than the photograph. These apparently contaminated areas are consistent with some of the Fe:Ca spikes in Fig. 7.1.19. These patches are common in the period prior to 1960 and could explain most of the Fe:Ca spikes before 1960. No patches of contamination are evident in the coral since 1960, so the Fe:Ca spikes in that part of the core remain unexplained. Similarly, 0.844 and 1.014 MeV peaks (Figs. 7.1.12 and 7.1.13) also show some relationship with patches of contamination in the coral skeleton.

(iv) Analytical error: Errors generated in the acquisition and processing of the PIXE data have been discussed extensively above. However, one point must still be made in the context of the Fe:Ca spikes. Although differences between replicate Fe peak area determinations were frequently high, they are relatively low when the Fe peak is high (Fig. 7.1.25). Because the differences between Ca replicates are low and the Fe:Ca values are largely determined by the Fe peak area, it follows that the values calculated for the high Fe:Ca spikes have low associated errors. The mean % difference between replicates for the four Fe peak areas > 60 in Fig. 7.1.25 is 22 %, suggesting that Fe peaks in this range have marginally acceptable precision. A similar relationship was evident in the PIGME results. This leaves unresolved the question of why the various PIGME spikes and Fe:Ca spikes do not occur on the same runs.

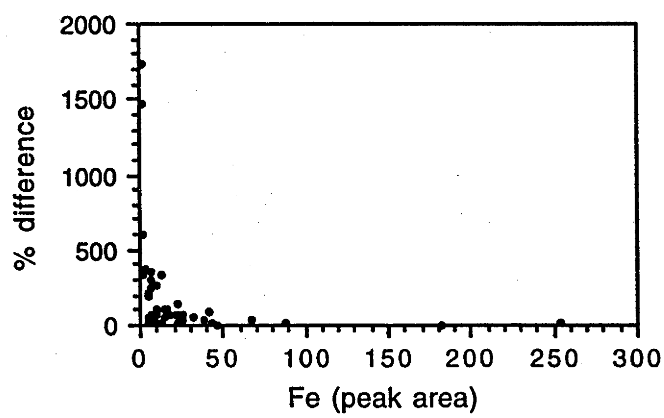


Fig. 7.1.25
Relationship between Fe peak area and the absolute % difference between replicate determinations (n = 47).

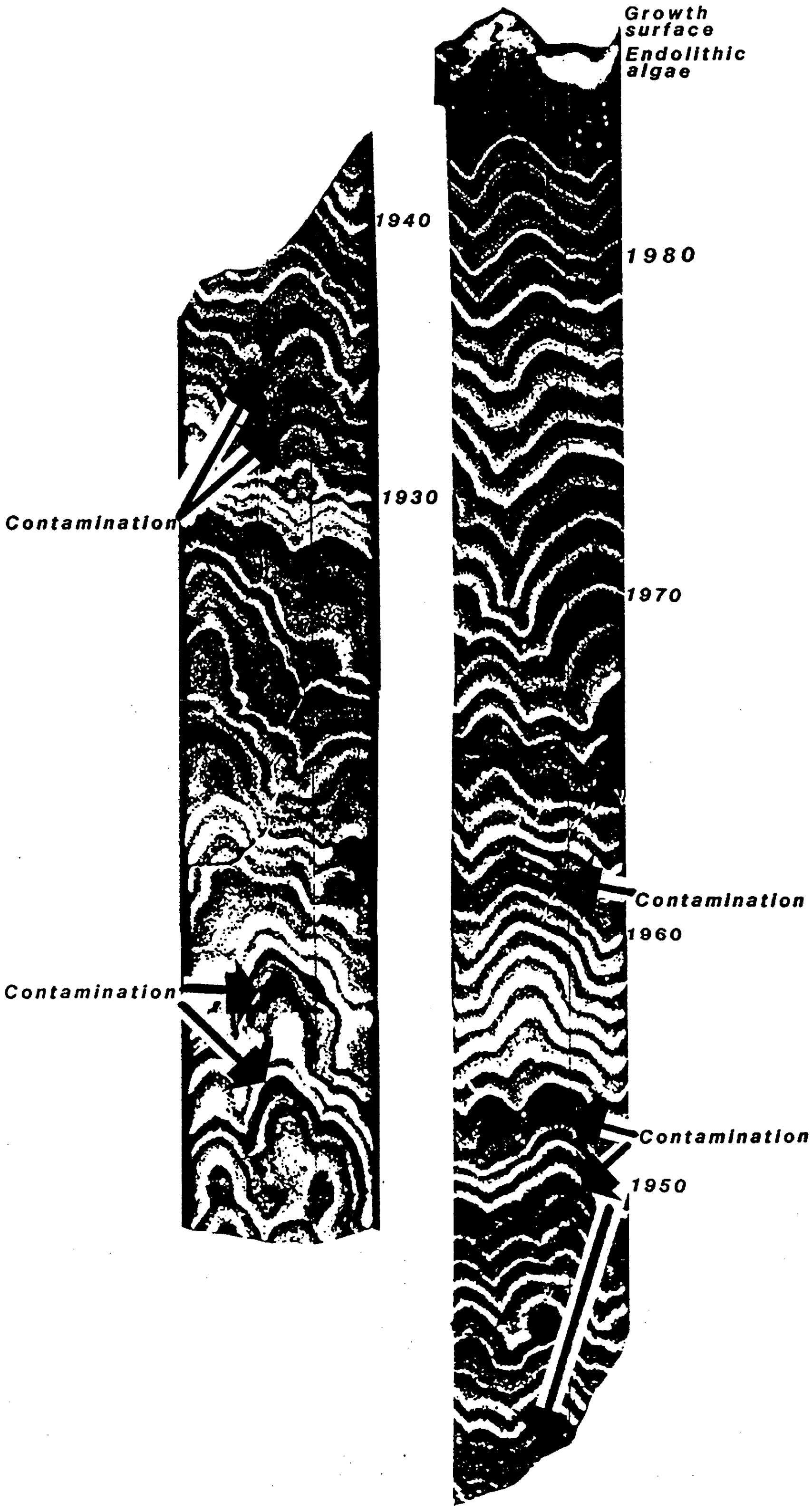


Fig. 7.1.24
Discolouration in the COO core consistent with contamination.

In summary, it appears that the time series of the ion beam analyses bear little relationship to the inferred sediment yield history of the Tully catchment. Neither is there any evidence of a relationship between inferred bottom resuspension and the PIXE/PIGME results. The results indicate that the peaks in the PIXE and PIGME time series relate generally to the periods in which sample contamination from endolithic boring was identified. The fact that individual PIGME and Fe:Ca peaks are poorly related in both timing and magnitude is interpreted as evidence of the strong contribution of analytical error to the results.

In the absence of any viable time series of sediment inclusions in the coral samples analysed, no attempt was made to construct a quantitative relationship between these inclusions and stream flow in the Tully River using either runoff modelling, stream flow relationships with adjacent streams or the stream flow relationship with skeletal fluorescence.

7.2 Nutrient time series.

7.2.1 Introduction.

Land use changed from forest to fertilised pastures and croplands generally results in increased stream nutrient loads, partly in direct response to increased soil loss and partly as a result of increased agricultural inputs. This trend is widely recognised in many areas of the world (eg. Roberts and Marsh, 1987). Probably the best known and best documented case of the effects of increased nutrient and silt concentrations in coral reef waters is that of Kaneohe Bay, Hawaii (Banner and Bailey, 1970; Banner, 1974) and subsequent studies of the effect of reduction of sewage inputs to the bay (Smith, 1977; Smith *et al.*, 1981). A major impact on Kaneohe Bay of this nutrient subsidy was an increase in the biomass of phytoplankton and zooplankton. Sedimentation of organic detritus generated by increased water column productivity allowed a large build up of benthic detritivorous biomass (Smith *et al.*, 1981). Corals were extensively replaced by benthic algae and the benthic filter feeders (eg. polychaetes, sponges, tunicates). Because many of the filter feeding organisms also excavate burrows from the coral substrate, the rate of physical destruction of the reef may also increase. Diffuse and discontinuous nutrient inputs, from agricultural runoff for example, are likely to result in algal overgrowth rather than destruction by reef boring biota as occurs in the more extreme case of sewage discharges (Kinsey, 1991b).

Increased nutrient concentrations are also reported to have a direct impact on coral skeletogenesis. At One Tree Reef, GBR, Kinsey and Davies (1979) showed that calcification rates could be reduced by 50 % at P concentrations of 2 μM. This concentration compares with a normal upper level of about 0.6 μM for 'healthy' open water reefs (Kinsey, 1991b). Rasmussen and Cuff (1990) showed that P concentrations of 2.0 μM are common in GBR waters in the Cairns/Port Douglas region and that calcification rates appear to have decreased and skeletal porosity increased in response to elevated P concentrations.

Rasmussen (1988) has also argued that skeletal Sr provides an index of P pollution because the Sr concentration in coral skeletons is "interrupted" in phosphorus polluted waters. The work of Schneider and Smith (1982) and of Muir (1984) is cited in support of this assertion. Schneider and Smith (1982) dismissed pollution (by groundwater discharge) as the source of a "Sr anomaly" (values c. 10 % lower than expected). Muir (1984) suggested that "external influences", including river discharges and trace chemical components, may have been responsible for the absence of an intra-annual relationship between seawater temperature and skeletal Sr concentration. No evidence was given to support this hypothesis. Rasmussen (1988) demonstrated that Sr concentrations in *Porites* species corals from Low Isles, GBR, decreased by 12 %, from 7 550 to 6 650 ppm, during a period of increased fertilizer application in adjacent catchments. It should be noted that almost half of this decrease occurred before significant application of P fertilisers commenced. The results are presented in approximately 5 year blocks and variation between contiguous blocks (eg. c. 1973 and c. 1978) is as much as 56 % of the overall decrease reported. In aquarium experiments, *A. formosa* skeleton had depressed Sr levels after the living coral had been subjected to elevated phosphorus levels in the form of superphosphate. A decrease of 5 % occurred at 2 $uM.L^{-1}$ P and at 3 $uM.L^{-1}$ P, the latter concentration only occasionally reached in these waters. Rasmussen (1988) concluded that the Sr concentration of coral skeletons is a useful quantitative index of levels of nutrient pollution in nearshore tropical marine ecosystems, although the qualifications presented above suggest that the argument is not entirely convincing.

Other environmental factors are also known to affect the Sr content of coral skeletons. Seawater temperature variations have long been known to cause variations in skeletal Sr:Ca ratios (Weber, 1973; Goreau, 1977a, b; Houck *et al.*, 1977; Smith *et al.*, 1979) resulting in the establishment of a palaeo-thermometer which is applicable in some environments, but not in others (Chivas, Aharon *et al.*, 1983; Muir, 1984). Weber (1973) outlines the lengthy and inconclusive debate over the validity of the Sr thermometer which occurred prior to publication of his comprehensive study. He also presents theoretical and empirical evidence for a significant growth rate effect on skeletal Sr concentrations. In contrast, Schneider and Smith (1982) found identical Sr:Ca ratios in a comparison of lateral and vertical growing sections of a *Porites* colony in which the lateral growth rate was 3 times that of vertical growth.

Variation of Ca content of the waters in which the coral is growing has been shown to cause a significant decline in the skeletal Sr concentration (Swart, 1979), although the partition coefficient remains unchanged. It is possible, therefore, that influxes of, for example, river water to the coral growth environment may result in Sr concentration variations not attributable to either temperature or nutrient pollution. While it could be argued that skeletal fluorescence could be used to account for freshwater effects on skeletal Sr concentrations, the evidence presented in Chapter 6.2 suggests that this is not necessarily so because river derived freshwater and humic acids each behave in a different way.

Mechanisms for trace element inclusion in corals remain the subject of discussion. Shen and Boyle (1988) have suggested that trace elements may be incorporated by direct substitution for Ca^{2+} in such cases as Pb, Cd and Mn and that lattice-compatible trace element uptake occurs in a regular, predictable manner, independent of "vital" effect. They also suggest that metals occurring in seawater in the 3^{+} state first require reduction if they are to be incorporated by direct substitution, a mechanism for which could be the fixation of CO_2 by zooxanthellae. The evidence available suggests that there are limitations to a simple co-precipitation model of incorporation and that, in many cases coral metabolism and algal photosynthesis play a significant role in mediating uptake (e.g. Thompson and Livingstone, 1970; Veeh and Turekian, 1968). In the case of Ra and U, for example, Flor and Moore (1977) have shown that these elements are first concentrated in the coral tissue from where they are carried into the skeletal framework.

Changes in water quality can stress corals in ways which affect many aspects of metabolic performance and the status of the zooxanthellae (Brown and Howard, 1985). Corals have also been shown to develop a tolerance to such factors as metal pollution (Harland and Brown, 1989). Consequently, partition coefficients for trace elements for which there is biological mediation may not be constant. There are further complexities in that elements such as U (Cross and Cross, 1983; Flor and Moore, 1977) and V (Shen and Boyle, 1988) are incorporated in coral skeletons, despite occurring as anionic complexes in seawater (Shen and Boyle, 1988; Swart and Hubbard, 1982).

Substantial diurnal variations in calcification rates, linear extension rates and crystal morphology have been documented (Barnes and Crossland, 1978; Gladfelter, 1982; Le Tissier, 1988). Le Tissier (1988), using qualitative EDX micro-analysis, showed that the elemental spectra of skeleton deposited at night differed from that during the day. This implies that trace element incorporation mediated by zooxanthellae may exhibit quite different responses to environmental changes than incorporation mediated by the coral, both of which may differ from incorporation by direct substitution.

In this section the use of coral cores from Rockingham Bay as recorders of nutrient yields from the Tully catchment is investigated.

7.2.2 Methods:

Preliminary analyses of the coral skeleton were made using the methods described in Ch. 7.1.2.1. Nutrient concentration time series in the coral cores were determined using the same general approach as for sediment inclusions, that is ion beam analysis using the PIXE and PIGME methods, described in Chapter 7.1.2.2 and 7.1.2.3 respectively. Pre-processing of the coral skeleton was described in 7.1.2.4. The reasons for utilising this approach were also outlined in Chapter 7.1.

Of the major nutrient elements of interest (N,P,K), nitrogen is too light to be detected by the PIXE method, phosphorus is similar to Si, being too light to yield a strong signal and with X-rays strongly diminished by the Al filter, and potassium X-rays are strongly absorbed by the Al filter and the K absorbtion edge is sufficiently close to that of Ca to partially mask any K X-rays. Consequently, any determinations of nutrient concentration using ion beam analysis were reliant on PIGME.

Strontium X-rays, on the other hand, occur at much higher energies than Ca and therefore are unaffected by proximity to the Ca absorbtion edge. Use of the Al filter to diminish Ca counts at the detector allows detection of relatively high Sr counts in practical running times. The differences between replicate Sr determinations were shown in Table 7.1.9.

The Sr:Ca ratios were severely affected by the marked discontinuities in the data described in Chapter 7.1.3.3. These discontinuities were dealt with by discarding all data sets except those for the KUB and BRO cores in which no discontinuities were detected. Note that the BRO core is that furthest from the Tully River, least likely to contain a fluvial signal and the most likely to be contaminated by river plumes from other sources, particularly the Herbert and Burdekin Rivers.

7.2.3 Results:

(i) Preliminary results: The major elements associated with fertiliser inputs to the catchment (N, P) were not evident in either river or coral derived residues analysed by SEM/EDX. A small K peak was evident in most samples.

Microprobe analysis showed that P and K concentrations in Bedarra Island coral samples were generally in excess of 150 ppm. There was no correlation between P and K concentrations in these samples.

Although the highest Si, Al and Fe concentrations were generally associated with areas of skeleton with strong UV fluorescence, this was not so for P and K.

(ii) Ion beam results: As expected from theoretical considerations, no N, P or K was detected in the PIXE spectra. Neither were any of these elements detected in the PIGME spectra analysed. As a result, nutrient concentration time series are available only by reference to variation in skeletal Sr, as suggested by Rasmussen (1988).

The time series of the Sr:Ca ratio in the KUB core, that most likely to be affected by Tully River inputs, shows that Sr:Ca ratio has declined since the mid-1950s (Fig. 7.2.1). The lowest Sr:Ca ratios, expected to be synchronous with the highest P levels, occurred during 1961 - 1965 and from 1974 to 1982.

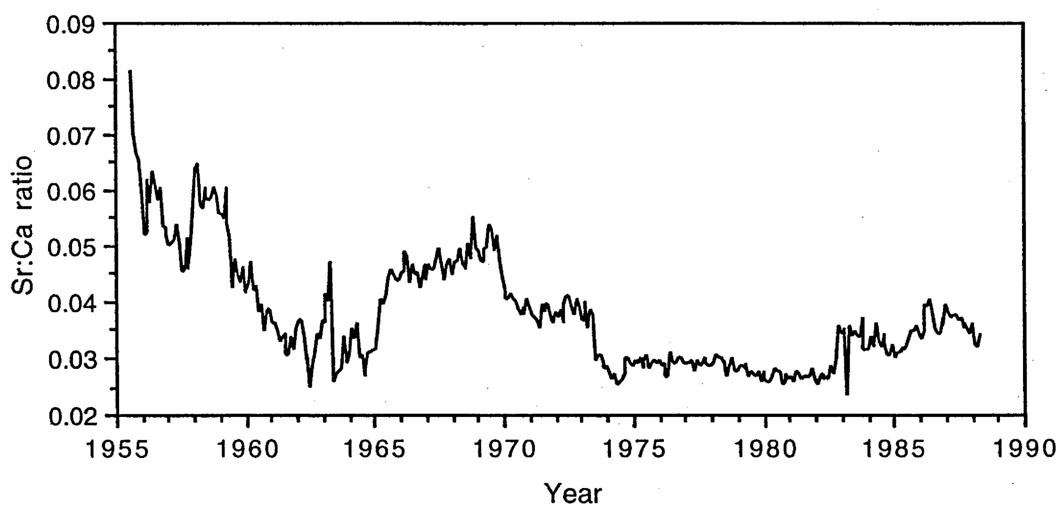


Fig. 7.2.1
Time series of Sr:Ca peak area ratios in the KUB core (1955 - 1988).

The Sr:Ca ratio pattern in the BRO core (Fig. 7.2.2) is similar to that of the KUB core with respect to the generally decreasing trend over time. However, there is little consistency between the two with regard to synchronous variation during the period of record. The maximum Sr:Ca ratio in the KUB core occurs in the late 1950s. The first half of the 1960s is a period of very low Sr:Ca. In contrast, the first half of the 1960s is a period of very high Sr:Ca ratios in the BRO core. Similarly, the 1980s is a period of increasing Sr:Ca ratios in the KUB core, and decreasing in the BRO core.

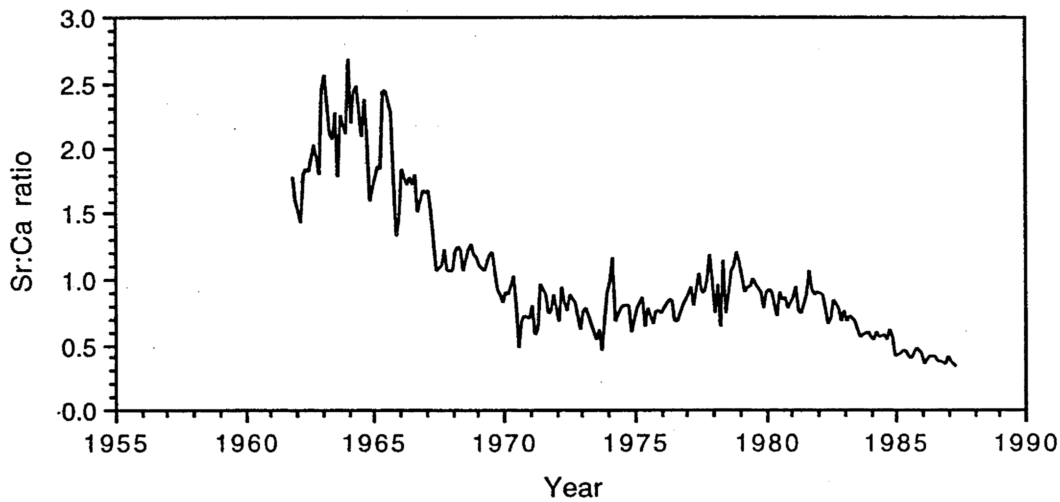


Fig. 7.2.2

Time series of Sr:Ca peak area ratios in the BRO core (1962 - 1988).

In Chapter 7.1.2.3 it was shown that Fe:Ca ratios are largely determined by the variation in Fe peak areas. This is not the case for Sr:Ca ratios, however. In both the KUB and BRO cores, Sr peak areas remained reasonably consistent while Ca peak areas varied considerably. Ca peak area explains 95 % of the variance in the Sr:Ca ratio (KUB core) and 90 % in the BRO core.

Although the inferred errors in both Ca and Sr determinations are acceptably low (Table 7.1.9), the inconsistency between the results from the two cores suggests that the Sr:Ca ratio variation in Figs. 7.2.1 and 7.2.2 may be related to factors other than changing water quality.

7.2.4 Discussion:

The results of the PIXE analysis of Sr:Ca ratios in Rockingham Bay corals are inconclusive. Data from only two of the four cores on which Sr:Ca ratios were determined are considered of adequate quality. This is a subjective judgement and some doubt about the contribution of analytical error to the results from these two cores remains.

The temporal pattern in the KUB core Sr:Ca ratio (Fig. 7.2.1) is not consistent with either the ABS fertiliser application time series (Fig. 2.3.7) or the fertiliser sales data (Fig. 2.3.10). Both of these data sets show a maximum nutrient input in the period since 1973 with the application rate reasonably constant through the 1980s. This pattern may have a parallel in the Sr:Ca series in the KUB core in a slight Sr:Ca "recovery" in the 1980s which could be attributed to such factors as relatively few floods carrying nutrients into fringing reef waters during this period or adaptation of the corals to higher nutrient levels. Neither of these explanations is particularly plausible. The peak in P application in 1980 reported by J. Pulsford (1993, pers. comm.; Fig. 2.3.10) has no geochemical equivalent in the coral skeleton. Similarly, the steady decline in the Sr:Ca ratio from 1955 to a minimum in the 1961 - 1965 period has no parallel in the nutrient input time series (Figs. 2.3.7 and 2.3.10).

As in the KUB core, the general pattern of the Sr:Ca ratio in the BRO core (Fig. 7.2.2) is not consistent with either the ABS fertiliser application time series or the fertiliser sales data (Figs. 2.3.7 and 2.3.10). Neither is there any apparent response to the peak in P application in 1980 (Fig. 2.3.10).

In principle, there should be little or no change in the Sr:Ca ratio in the BRO core because river waters seldom reach this site, as indicated by sediment plume dynamics (Chapter 5) and by the spatial pattern of skeletal fluorescence (Fig. 6.2.1). If Ca concentrations are assumed reasonably constant, the changes in Sr:Ca ratios suggest a decrease in Sr concentration by about 400 - 500 % which, particularly in the case of the BRO core, is clearly nonsense.

Given that:

i. the inconsistent results between the Sr:Ca ratios of the KUB and BRO cores are not caused by differences in the water quality they are sampling,

ii. the range of variation in Sr concentrations implied by the PIXE results is implausible, and

iii. the major determinant of the Sr:Ca ratio is variation in the Ca peak area,

it seems likely that the principle cause of variation in the Sr:Ca ratio is variation in skeletal morphology and/or analytical error. Although there is no relationship between Ca peak area and skeletal density in either core, this is not surprising as the PIXE data reflect surface characteristics, whereas skeletal density is averaged over the 7 mm slice thickness.

Greater energy of the X-rays emitted from proton collisions with Sr than with Ca atoms results in a Ca time series which is much more sensitive to skeletal morphology than is that for Sr. This differs from the contrast between Ca and Fe in which the energies of the emitted X-rays are very similar.

The unreliability of the PIXE determinations is confirmed by comparison with the Sr:Ca time series from Pandora Reef (McCulloch *et al.*, in prep.). Although corals at this site record Burdekin River runoff (Isdale, 1984; Fig. 6.2.3), there are no significant excursions, which could be attributed to the effects of river plumes, from the strong seasonal signal which correlates with seasonal variation in sea surface temperature. By contrast, the PIXE Sr:Ca time series from both Kumboola and Brook Islands are dominated by unexplained excursions and the seasonal signal is uncertain. The very high inter-annual consistency of McCulloch *et al.*'s Sr:Ca results, which include the effects of major Burdekin floods in 1979 and 1981, also casts doubt on the reliability of skeletal Sr as a recorder of P concentrations in reef waters.

It is concluded that the patterns of variation in the Sr:Ca time series are largely a consequence of variation in surface morphology of the coral skeleton. This morphological variation is probably due to both the chance relationship between the position of the cut face and the skeletal morphology, and to temporal variation in coral morphology. Consequently, these results do not contribute to Rasmussen's hypothesis regarding the role of strontium concentrations in coral skeleton as an environmental indicator, but do confirm the limitations of surface analysis techniques applied to coral skeleton.

7.3 *Summary.*

Although there are research findings which indicate that coral skeletons contain a record of terrigenous sediments (e.g. Barnard, Macintyre and Pierce, 1974; Cortes and Risk, 1985), there are several others which indicate the contrary (e.g. Goreau, 1977a, b; Benninger and Dodge, 1986; Davies, 1992, in prep.; Budd *et al.*, 1993). In general, the limitations are seen to arise from uncertainties regarding the mechanisms by which sediments are incorporated into the coral skeleton, and the errors induced by contamination through boring by endolithic organisms. Results of this analysis show that detritus of inorganic, terrigenous origin is incorporated into nearshore coral skeletons from fringing reefs off the northeast Queensland coast. Concentrations of these inclusions are too low for precision gravimetric analysis at a sub-annual time scale. Furthermore, the presence of acid-insoluble detritus of marine origin would not allow accurate gravimetric determination. The PIXE/PIGME methods of ion beam analysis were applied because of these limitations, and because of the desirability of using a scanning technique for continuity of the sediment inclusion time series.

However, the determination of temporal variations in the concentration of sediment inclusions in the coral skeleton, using the PIXE/PIGME method, has been shown in the preceding pages to have limited application with respect to reconstruction of sediment yields from terrestrial catchments. These limitations arise from the following :

i. Limitations of the PIXE/PIGME method:

These limitations, discussed in Chapter 7.1.3.3, are largely a function of the minimum detectable limits of the method for the relevant elements, which occur at low concentrations. Also of importance is the effect of varying skeletal morphology on the X-ray emissions which, in turn, varies between elements.

ii. Limitations of the particular PIXE/PIGME equipment used for the analyses:

These limitations, also discussed in Chapter 7.1.3.3, were evident during determinations as inconsistent running conditions and other technical problems, and are evident in the results as large discrepancies between replicate analyses, unexplained discontinuities in the time series results, and inconsistencies between the PIXE and PIGME time series.

iii. Problems of contamination in the coral skeleton by endolithic borers, uncertainties as to the mode of sediment inclusion, and uncertainty as to the relative importance of wave resuspended sediment and sediment of fluvial origin. These problems are independent of the analytical method used.

The limitations described in i. and ii. above also apply to the determination of Sr concentrations. The results obtained are clearly spurious, probably related to variation in surface morphology of the coral slice.

It seems clear that the PIXE/PIGME method has limited, if any, application to the reconstruction of sediment and nutrient yield time series from terrestrial catchments using coral geochemistry. However, an alternative strategy is suggested which may yield a useful sediment yield time series. Given the reservations expressed in Chapter 6 regarding the ability of the skeletal fluorescence record to provide a sub-annual record of stream flow and the absence, at the present time, of any other method of deriving a sub-annual stream flow series, the quest for a sediment yield record at a sub-annual time scale is largely irrelevant. Given that sediments consistent with a fluvial origin have been shown to be present in the

Rockingham Bay corals and Al is diagnostic of those sediments, an annual series of sediment inclusion based on the determination of Al concentrations in bulk samples of annual increments of coral skeleton should yield a sediment yield time series at annual increments. The difference in Si:Al ratios between river sediments and coral sediments (Table 7.1.3) suggests that this analysis could be extended to provide an annual series of both stream sediment yield and bottom sediment resuspension. Such an analysis would still be subject to the limitations imposed by sediment inclusion mechanisms and by contamination, and the cautions of Budd *et al.* (1993) regarding intra- and inter-colony variation in concentrations of insoluble residue.

CHAPTER EIGHT

CONCLUSION

This chapter outlines the main findings of the preceding chapters, emphasising those which are most relevant to the task of developing a long-term record of the sediment yield response to land use intensification in the wet tropics using annually-banded massive corals as environmental recorders. These findings are as follow:

(i) Catchment physiography, climate and land use

* Lithology of the Tully River catchment is predominantly granitic. A little less than one third of its area is Quaternary alluvium, and land use intensification is largely confined to these areas. There is a very strong association between land use and the lithology, topography, soils, and climate of the catchment.

* Although there is considerable morphological evidence of stream channel instability during the Holocene, evidence from historical maps suggests that during the historical period the Tully River channel has been stable.

* Only minor changes in Tully River channel morphology have occurred over the last two decades, the period for which data are available. The data indicate slight narrowing and deepening of the channel, rather than the aggradation suggested anecdotally by local residents. Several factors, including episodes of land clearing, levee construction, sand and gravel extraction, increased suspended sediment concentrations, rainforest removal from stream banks, and colonisation of stream banks by introduced grasses, may have contributed to the subtle changes in channel morphology which have occurred. No significant change in hydraulic efficiency of the Tully River is likely.

* Mean annual rainfall at Tully is 4 188 mm (1925-1991), ranging from 2 489 to 7 899. Rainfall decreases south of Tully and inland, but increases with elevation. Seasonal rainfall erosivity patterns are hysteretic, with the highest relative erosivities in the December - January period. Rainfall erosivity is at its highest during February and March. There is a decreasing trend in rainfall erosivity at Tully since the late 1940s, also evident elsewhere in the humid tropics of northeast Queensland, which may have influenced the sediment yield over the last half century.

* Mean annual runoff from the Tully catchment is about 2 200 mm, or 74 % of the catchment mean annual rainfall. Regional comparison shows the runoff coefficient to be high, and the inter-annual variation in stream flow to be low. This low inter-annual variability is ideal for assessment of the effect of land use intensification on sediment yields.

* There is circumstantial evidence that lowland vegetation at the time of European settlement was strongly influenced by previous Aboriginal land management practices, particularly burning. Sediment yields from the Tully catchment prior to European settlement could not be regarded as "natural".

* Although the earliest agriculture took place in 1866 in the lower Murray, the first significant land use intensification, for cane growing, occurred following construction of the Tully Sugar Mill in 1925. Large-scale land clearing for pasture occurred during the early 1960s, there was a further cane land expansion in the late 1970s, and banana cultivation has steadily increased since that time. The relatively recent land use intensification at discrete times is important because more data are available, more than one episode of land use intensification can be monitored, and shorter coral cores are required.

* Significant changes in cultivation practices, largely associated with cane harvesting, have taken place during the post-settlement period and are likely to have reduced sediment yields. However, Tully cane growers have the lowest rate of adoption of conservation techniques in the north Queensland wet tropics, with only 25 % of canelands managed this way in 1990.

* Application rates and areas fertilised have increased significantly over the last forty years. The greatest increase has occurred in areas under banana cultivation. The increased nutrients in coastal waters are likely to have affected both the physiological responses and skeletal structure of the corals.

(ii) Land use and water quality

* Good estimates of both the suspended sediment and solute concentrations in the Tully River can be obtained from nephelometers and conductivity meters, respectively.

* Suspended sediment concentrations exhibit clockwise hysteretic behaviour in relation to stream flow, which is the commonly observed pattern.

* The anti-clockwise hysteresis of the solute concentration is a little unusual, but not unique to this catchment. Different components of the solute load exhibit markedly different patterns of behaviour in relation to stream flow.

* The relative importance of suspended and dissolved loads changes in favour of the suspended load contribution as stream flow increases and as the proportion of the catchment cleared increases.

* Colorimetric analysis of the suspended sediments showed that, at peak stream flows, about half of the sediment comes from in situ montane and colluvial soils, most of which retain a rainforest cover. At low stream flow and SSC most of the sediments are derived from alluvial soils.

* The spatial distribution of sediment concentrations in the Tully catchment indicates a significant increase in sediment concentrations associated with increasing areas of agricultural and pastoral land uses. Although this is clearly the case for agricultural land, implying an increase of about an order of magnitude for a completely cleared catchment, it is much less clear for grazing land for which a relatively small increase, perhaps by a factor of about two, is likely.

* There is a high level of variability in both sediment and solute load between catchments of apparently similar physical characteristics.

* Sediment yield in the Tully catchment is quite low by both regional and world standards. This is the case despite clearing of 8 % for agriculture and 12 % for improved pasture. Reasons for the low sediment yield include tectonic stability, low inter-annual rainfall variability, soils of relatively low erodibility and high permeability, the absence of land clearing on steeplands, and the adoption of zero tillage/residue retention cropping practices on about one-third of the Tully cane lands.

* In the context of sedimentation impacts on offshore coral reefs the effective increase in sediment yield is likely to be greater than the increase interpreted from catchment studies because the increase in sediment yield appears to be largest at the highest stream flows, and because land use intensification generally increases the hydraulic efficiency of catchments.

* The difference between the trend in estimated sediment yield due to changing catchment susceptibility to water erosion (Fig. 4.3.1; an increase by 240 %) and the trend in the reconstructed sediment yield, corrected for temporal variation in estimated rainfall erosivity (Fig. 4.3.2; a decrease by 40 %) may be significant. In analyses of spatial patterns of sediment yield, it is often argued that, within a climatic region, the effect of land use on sediment yield over-rides that of other catchment characteristics. These results suggest that, in the case of temporal patterns of sediment yield, rainfall erosivity trends within a region may be sufficient to obscure the effect of land use. Although further research is required to confirm the validity of the rainfall erosivity index, the decreasing trend since the 1940s is evident for all erosion thresholds used (Fig. 2.1.14), for rainfall.rainday^{-1}

(Neil and Brierley, 1990) and, to a minor degree, for total rainfall (Fig. 2.1.8), and the erosivity index is also strongly correlated with catchment runoff (Q_{60}) for the years for which streamflow data are available.

* Although the magnitude of the sediment yield response to land use change is comparable with that in many other catchments, it seems likely that the land use signal may be too small to be reliably discriminated within the naturally high variability of the erosion process. It is emphasised that this is the case even in a catchment of very low hydrological variability, such as the Tully.

(iii) Sediment plume characteristics

* Tully River sediment plume movement in Rockingham Bay is largely northward in close proximity to the coast, in accord with the documented role of wind-forced, nearshore currents and of geostrophic currents.

* Sediment plume movement is variable in response to variation in oceanographic conditions. However, winds from the southeast quadrant prevail during most floods maintaining the northward, nearshore transport of suspended sediments.

* There is some evidence of trapping of oceanic water against the coastline in the vicinity of Kennedy and Lugger Bays and of considerable sediment plume recirculation due to tidal action.

* The direct effect of the plume appears to occur predominantly in the vicinity of Bedarra, Timana and Kumboola Islands, although its presence at these sites is probably of only limited duration under favourable winds.

* The interpreted pattern of sediment plume movement is generally consistent with between-site variation in the UV fluorescence intensity of coral cores from Rockingham Bay, although the fluorescence intensity suggests a greater fluvial influence at Coomb Island than indicated by observations of sediment plume behaviour. This difference probably relates to the contrasting behaviour of river load in solution and river load in suspension.

* Bottom sediment resuspension appears to influence both sediment and nitrogen concentrations, particularly in the vicinity of the offshore islands, to the extent that river-derived sediment concentrations are likely to be indistinguishable from resuspended sediment concentrations. Increased sediment and nutrient concentrations at island sites indicate that water quality at these sites is influenced by local factors and is not representative of the surrounding marine environment in general.

* Sediment concentrations at island sites due to river plumes may be about twice as high as those from bottom sediment resuspension. However, bottom sediment resuspension appears to be more than ten times as frequent.

* The overlap between the timing of high onshore wind energy and high stream flow means that spatial separation of these two sediment types in the coral skeleton cannot be assumed.

* There are three patterns of solute and particulate distribution in Rockingham Bay waters for the parameters analysed. These are:

    1. Concentration maximum occurs in river waters with a decline offshore as mixing takes place (Si).

    2. Concentration maximum in river waters with a mixing forced decline offshore and an increase in the vicinity of the offshore islands as a result of bottom sediment resuspension (SSC and Total N) with implications for coral growth in the vicinity of continental islands and possibly for algal blooms in nearshore waters.

    3. Concentration minimum in river waters with an increase offshore as mixing takes place (Cl, SO_4, Mg, Ca, K, Na and Sr).

* The marked break in the slope of the relationship between SSC and salinity at 10 ‰ indicates that a high proportion of the suspended sediment is deposited in the immediate vicinity of the river mouth. A continued decline in SSC in relation to salinity < 10 ‰ suggests that suspended sediment continues to be lost from surface waters in excess of the mixing rate, in contrast to the reported pattern in the Burdekin plume.

(iv) Coral skeletal fluorescence

* Fluorescence intensity in massive corals provides a good measure of fluvial discharge from the Tully catchment, which differs markedly in lithology, vegetation and land use from the Burdekin catchment for which Isdale (1984) has published results.

* The slightly lower correlation between UV fluorescence and discharge for the Tully River-Rockingham Bay case than for the Burdekin River-Pandora Reef relationship is attributed to both the lower inter-annual variability of the Tully River discharge and the likely greater variability in the direction of movement of the relatively small Tully River plume.

* Averaging fluorescence data from several relevant sites, thereby taking some account of variation in river plume movement, leads to an improved correlation between UV fluorescence and discharge.

* The results suggest that variations in the sediment concentration-discharge relationship may influence transport of humic compounds to

reefal areas, slightly altering the skeletal fluorescence - stream flow relationship.

* In general, best relationships between skeletal fluorescence and stream flow will be obtained by using multiple cores from carefully selected sites. This is likely to be more important in small catchments such as the Tully than in very large catchments (eg. the Burdekin) because of the more restricted distribution of small-catchment river plumes. The higher the seasonality and the higher the inter-annual variability, the better will be the statistical relationship between coral fluorescence and stream flow.

(v) Coral skeletal inclusions

* Preliminary analyses of massive coral skeletons from fringing reefs offshore from the Tully River contain acid-insoluble residues which are elementally and mineralogically consistent with a fluvial source, possibly the Tully River. The Al is particularly diagnostic, given the absence of primary Al-bearing particulates in the marine environment. The broad quartz peak in the XRD spectra is attributed to amorphous silica with a probable marine origin, rather than terrigenous sources. The Fe present in the corals could be derived directly from soils of the Tully catchment and adjacent islands, indirectly from resuspension, precipitated from solution, or co-precipitated with fulvic and humic acids, but is not associated with the clay minerals present. Consequently, neither Si nor Fe are diagnostic of terrigenous inputs.

* For high resolution analysis, a surface scanning technique is highly desirable. Although PIXE/PIGME is such a method, it is unsuitable for sediment inclusion analysis of coral skeletons because the minimum detectable limits of the method for the relevant elements, which occur at low concentrations, are too high. Surface analysis techniques are also affected by varying skeletal morphology which Rasmussen and Cuff (1990) suggested is itself an indirect response to land use intensification. In the case of X-ray emissions the effect of variation in skeletal morphology differs between elements.

* Contamination in the coral skeleton by endolithic borers, uncertainties as to the mode of sediment inclusion, and uncertainty as to the relative importance of wave resuspended sediment and sediment of fluvial origin all confound the interpretation of catchment sediment yields from coral skeletons.

* The results of this study are consistent with recent research results. Davies' (1991; 1992; in prep.) work concentrated on the biological aspects of sediment incorporation into coral skeleton. Budd *et al.* (1993) place much of

their emphasis on the corals *per se,* but in the context of limited environmental data. The present study places considerable emphasis on the environmental context. The findings of all of these studies, each with a quite different approach, are consistent and lead to the same general conclusion.

* A high-resolution record at sub-annual time scales of suspended sediment concentrations, which can be directly, quantitatively and chronologically correlated with fluvial sediment yield, is unlikely to be reliably obtained from coral skeletons.

* Given that sediments consistent with a fluvial origin have been shown to be present in the Rockingham Bay corals and Al is diagnostic of those sediments, an annual series of sediment inclusion based on the determination of Al concentrations in coral skeleton should yield a sediment yield time series at annual increments. The difference in Si:Al ratios between river sediments and coral sediments suggests that this analysis could be extended to provide an annual series of both stream sediment yield and bottom sediment resuspension. Problems related to contamination and sediment inclusion mechanisms would still apply.

Several aspects of the geomorphic and ecological systems analysed indicate that massive corals have poor prospects as high resolution, long term recorders of catchment sediment yield. Table 8.1 provides a summary of these limitations. Some of these limitations are likely to be of greater importance in the Tully catchment than elsewhere, others less so.

(vi) Application of research methods:

* Wherever feasible, methods used in this research were deliberately kept simple, requiring the minimum technical sophistication which would yield satisfactory results. It is hopeded that the questions investigated herein may be be investigated in other catchments by individuals or organisations lacking financial resources and/or technical resources and skills.

* Examples of potential users include Land Care and Integrated Catchment Management groups in Australia, and environmental management agencies in developing countries.

* Examples of these research methods include:

i. The estimation of spatial variation in sediment and solute loads using random, spot sampling at numerous sites on numerous occasions.

ii. The simple monthly runoff model using only monthly rainfall and mean monthly evaporation at a single site as input variables.

iii. The estimation of long term variation of rainfall variability using simple manipulations of daily rainfall data

iv. Colourimetric sediment sourcing in humid tropical catchments.

Characteristic	Limitation
Catchment characteristics:	
	* Both long term trends and inter-annual variation in climate, particularly rainfall erosivity, may mask the sediment yield response to changing land use.
Oceanographic characteristics:	
	* Most fluvial suspended sediment is deposited close to the river mouth.
	* The prevailing wind during most floods forces sediment plumes away from the fringing reefs and towards the mainland coast.
	* Bottom sediment resuspension, rather than fluvial sediment, is the source of most of the suspended sediment at island sites in Rockingham Bay.
	* Fidelity of a particular coral colony to a specific stream cannot be assumed.
	* The position of the calcifying coral surface in relation to vertical gradients of plume and bottom sediments changes over time.
Coral skeletal fluorescence record:	
	* The fluorescence record has insufficient temporal resolution for studies in process geomorphology.
	* The fluorescence record may be affected by skeletal contamination, variation in porosity and in suspended sediment concentration.
Coral bio-geochemical characteristics:	
	* Several mechanisms of detrital inclusion are possible.
	* Some mechanisms involve biological mediation, others do not.
	* Adaption of corals to changing environmental conditions is likely to affect biologically-mediated inclusion mechanisms.
	* Synergistic effects of combinations of stressors including sedimentation are likely to affect biologically-mediated inclusion mechanisms.
	* Particulate contaminants move vertically and laterally, dominantly the latter, in the coral skeleton.
Surface analysis techniques:	
	* Natural variation in skeletal void space occurs.
	* Variation in skeletal void space is itself affected by land use change.
	* Concentrations of relevant elements in coral skeleton are at the limits of PIXE/PIGME resolution.

Table 8.1
Summary of limitations in the determination of sediment yield from records in massive corals.

Conclusion:

This research has shown that a reliable separation of the anthropogenic component from the natural sediment yield in the Tully River catchment is unlikely to be possible using an environmental recorder such as massive corals while retaining a high temporal resolution record. The complexity of sediment plume movement, mixing, and the gradually changing position of the calcifying coral in the water column further compound the limitations of the method. Continued uncertainties as to the mechanisms of sediment incorporation into massive corals, combined with the likelihood that an unknown proportion of any sediments which are incorporated are effectively contamination, render the proposed environmental recorder unreliable. The necessity for the coral colonies sampled to be located in the nearshore zone imposes further limitations due to both the geomorphic and ecological characteristics of that zone, particularly the frequency of bottom sediment resuspension, endolithic boring, partial colony mortality and generally small colony size.

Resuspended sediment is the major source of noise in the nearshore water quality. Because of the irregularity of this noise, large numbers of measurements in a continuous time series are needed to discriminate between resuspended sediment and fluvial sediment. The PIXE/PIGME method is suited to the high frequency time series analyses which are necessary, but does not have the sensitivity to detect the relevant elements at the concentrations at which they occur in the coral skeleton.

Prospects for a sediment yield record in massive coral skeletons appear to lie in three areas. Firstly, the good relationship between skeletal fluorescence and stream flow suggests that a chemical signal of the anthropogenic component of sediment yield may be more successful than direct sediment inclusion for deriving a high resolution record. Secondly, although the Tully catchment is ideally suited to this investigation in many respects, the increase in sediment yield due to land use intensification is much lower than in other catchments where a greater proportion of the catchment or steepland has been cleared. Catchments with a greater sediment yield increase would be likely to yield a much stronger signal in any environmental recorder. Thirdly, a record at the annual time scale using direct sediment inclusion and analysis of Al concentrations may still prove to be a useful environmental indicator. When combined with Si determinations, such a record may also provide a time series of bottom sediment resuspension.

In conclusion, results suggest that a high resolution record of suspended sediment concentrations which can be quantitatively related to fluvial sediment yield at sub-annual time-scales is unlikely to be obtained from coral skeletons using scanning methods. However, extraction of acid-insoluble residues in annual bands has some promise, and further investigation of this possibility is recommended.

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